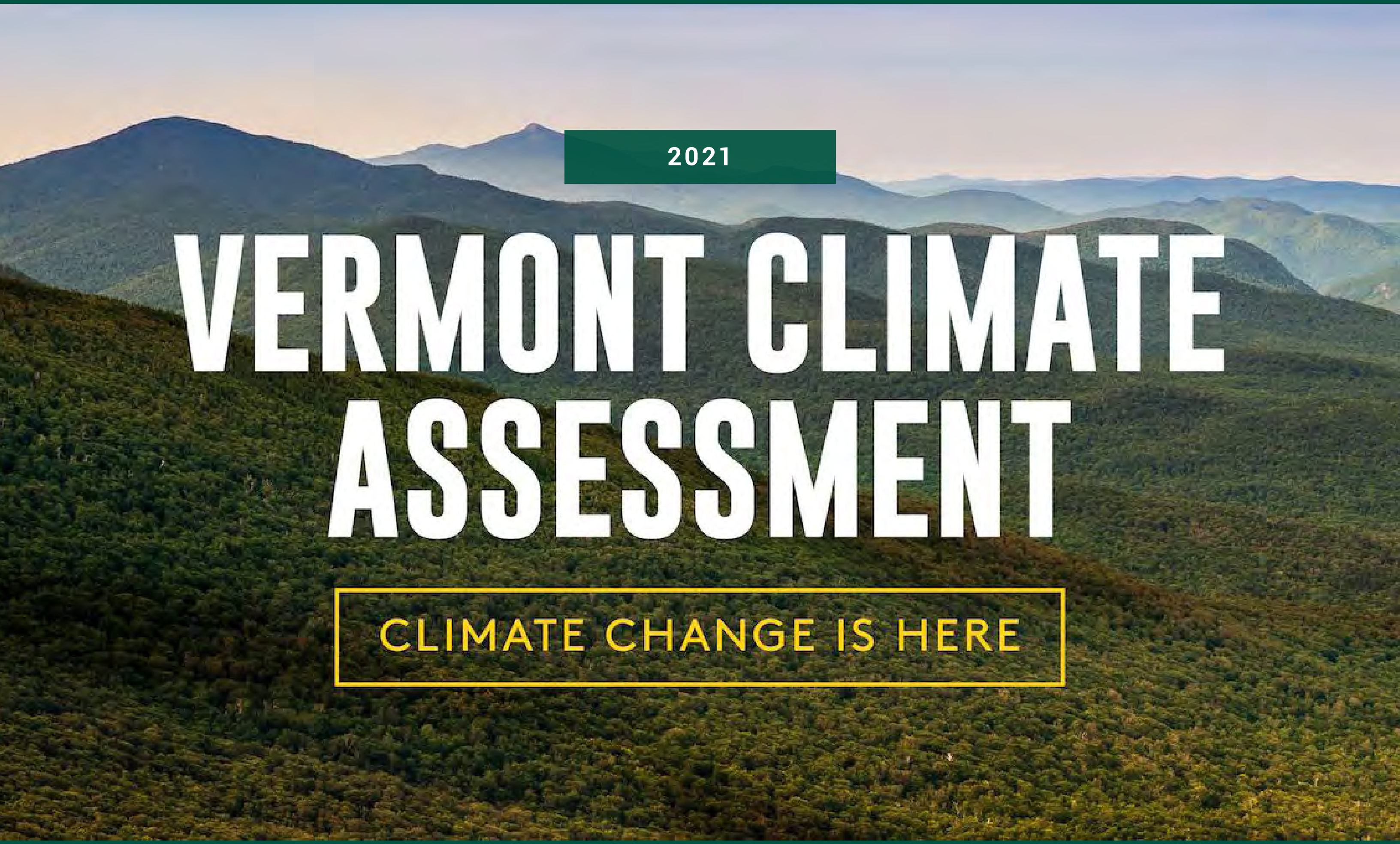
See full report: vtclimate.org



2021

VERMONT CLIMATE ASSESSMENT

CLIMATE CHANGE IS HERE

ABOUT THE VERMONT CLIMATE ASSESSMENT

The Vermont Climate Assessment (VCA) provides a framework for understanding climate change impacts in Vermont. It is written to help citizens and decision-makers make sense of climate data and prepare for future impacts across key sectors (for example, the Vermont Climate Council, which is working to reduce the state's GHG emissions and identify actions Vermont communities can take to better prepare for more extreme weather). The VCA 2021 updates the University of Vermont's pioneering state climate assessment in 2014, which was the first to provide state-level data similar to the National Climate Assessment.

The VCA 2021 included a process to engage key stakeholders from the beginning of the assessment. Understanding stakeholder interests enabled the VCA team to focus on relevant, useful research. Researcher Laura Edling led a needs assessment in 2020 to:

- Understand what VCA information would be most useful and why;
- Facilitate ongoing knowledge exchange among VCA researchers and a variety of stakeholders; and
- Identify diverse sources of knowledge that are relevant to climate research and decision-making.

Many stakeholders were interested in impacts related to precipitation, storms, and flooding. For example, stakeholders in the agriculture sector expressed a desire to know "will my field flood" and requested data that could help them plan infrastructure upgrades and drainage strategies. The VCA 2021 report aims to further local understanding of climate change and its impacts and provide climate information that is used and useful.

VERMONT CLIMATE ASSESSMENT

The University of Vermont

GUND INSTITUTE FOR ENVIRONMENT

The Nature Conservancy

RECOMMENDED CITATION

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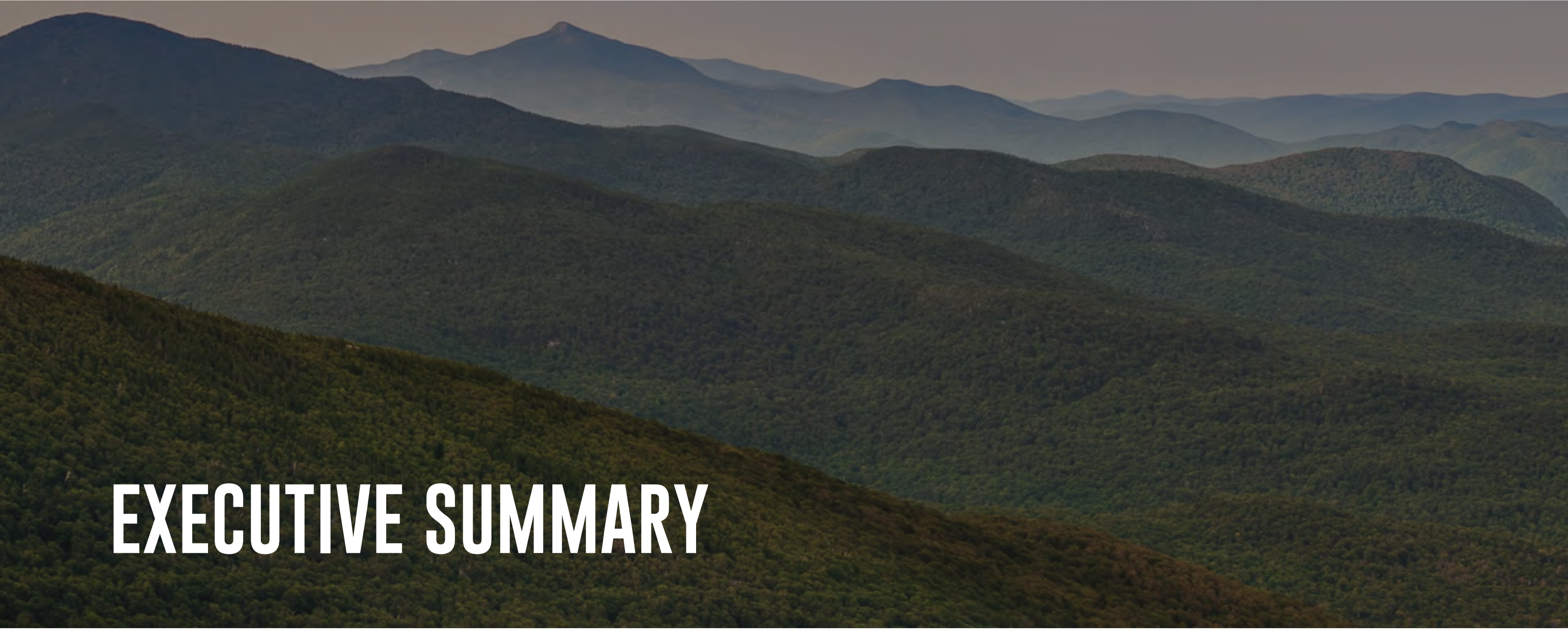

EXECUTIVE SUMMARY

> “The impacts of climate change are already being felt in communities across the country.”
>
> -Fourth National Climate Assessment, U.S. Global Change Research Program, 2018

The Earth’s climate is changing. Data for the past several decades show long-term shifts in temperature, precipitation, and the risks of certain types of severe weather. As climate change unfolds, it is important to understand the impacts globally and locally here in Vermont.

The Vermont Climate Assessment 2021 (VCA) assesses the science of climate change and its impacts across Vermont. The VCA examines what climate change means for different sectors in Vermont and summarizes what we know about possible climate futures. It represents our current best understanding of climate change in Vermont.

This executive summary is a high-level overview of the underlying report. The VCA highlights the following main findings.

CLIMATE CHANGE IS HERE.

There is strong evidence that Vermont's climate is changing. Vermont is becoming warmer (average annual temperature is about 2°F warmer since 1900), and Vermont's winters are becoming warmer more quickly (winter temperatures have warmed 2.5x more quickly than average annual temperature since 1960). Vermont is also becoming wetter (average annual precipitation has increased by 21% or 7.5 inches since 1900). However, Vermont still experiences prolonged droughts because of shifts in the water cycle, and different regions of Vermont can experience different climate impacts. The data for Vermont mirror trends at the regional, national, and global scale.

CLIMATE CHANGE IS IMPACTING COMMUNITIES ACROSS VERMONT. PEOPLE ARE RESPONDING.

Climate change is transforming people's lives in Vermont, now and in the future. This report and others like it are increasingly documenting climate risks and vulnerabilities. For example, rivers overflowing from more rain increases risks of flooding that can damage homes, roads, bridges, and farm fields. Heavier rainstorms impact farm and forestry operations. Climate change affects people's recreation year-round: Vermont's ski season is shorter, spring activities are disrupted by more rain than in the past, and summer recreation faces increased risk of harmful algal blooms in lakes. And climate-related health impacts – greater risk of heat exposure, water and air quality issues, and natural disasters – threaten some parts of the population more than others, highlighting the unequal burden of climate impacts for people who are over 65, of low socioeconomic status, or have previous health issues. People are responding, for example by resizing culverts, riding snowmobiles less, storing piles of snow in attempts to extend the Nordic ski season, and managing water differently in farm fields. In planning for climate impacts, communities cannot assume that future climate conditions will resemble the past.

THERE ARE INTERACTIONS AMONG CLIMATE IMPACTS.

Multiple stressors can stack up to have an outsized effect on people and nature. Continuing to study these issues will help us understand how multiple, interacting factors will affect strategies designed to lessen climate impacts. For example, drought plus the spread of invasive pests could interact to stress trees and diminish the ability of forests to capture and store carbon from the atmosphere. We can anticipate some interactions among climate impacts; we will be surprised by other interactions that are difficult to predict. Interactions could push natural systems past tipping points, or limits in long-balanced ecosystems after which drastic changes lead to completely different systems. The long-term, persistent, and complex nature of climate change can also intensify other stresses on society, such as managing public health crises or confronting social inequities.

THE VCA 2021 UPDATES – AND IS LARGELY CONSISTENT WITH – THE ORIGINAL VCA 2014 STUDY.

The 2021 report builds from pioneering work completed in VCA 2014, the first state-level climate assessment in the U.S. Conclusions between the 2014 and 2021 reports are consistent. With additional data and new tools for visualizing climate change, the VCA 2021 finds:

- Vermont's average annual temperature increase since 1960 is 1.47°F compared to the previous estimate of 1.3°F.
- Vermont's average annual precipitation increase since 1960 is 6.71 inches compared to the previous estimate of 5.9 inches.

The VCA 2021 features new data that provide further evidence of warming in Vermont, including plots that show fewer cold days (max temperature less than or equal to 0°F) and more warm winter days (max temperature greater than or equal to 50°F during winter months). VCA 2021 incorporates new data to show how Vermont is experiencing 2.4 more days of heavy precipitation since 1960 (days with precipitation greater than or equal to 1 inch).

INFORMATION ABOUT CLIMATE IMPACTS IS VALUABLE FOR VERMONT DECISION MAKERS.

Planning for climate change requires sound scientific evidence. The VCA provides information on climate change and its impacts at scales relevant to policy and decision making. The information in this report can inform many decision makers in Vermont, from individual farmers to town highway departments to regional planning councils to state agencies. Bringing global and national climate assessment techniques to the state-level equips local stakeholders to make decisions based on scientific data. For example, the Vermont Climate Council is responding to concerns about Vermont's changing climate. Without action and investment, climate-related impacts and risks will continue to grow for current and future generations.

THE FOLLOWING KEY MESSAGES SUMMARIZE THE EVIDENCE AND MAIN FINDINGS FROM THE VCA 2021 REPORT.

1 CLIMATE CHANGE IN VERMONT

1.1 Vermont's annual average temperature has increased by almost 2°F (1.11°C) since 1900. Winter temperatures have increased 2.5 times faster than annual temperatures over the past sixty years, and the number of very cold nights has decreased by over seven days in the same time period.

1.2 Average annual precipitation in Vermont has increased by 21% since 1900 and has become more variable in the last decade. Annual snowfall has been decreasing since the 1960s, yet winter precipitation has increased, suggesting that more winter precipitation is falling as rain.

1.3 Vermont's freeze-free period has lengthened by three weeks since 1960; the trend has accelerated to an increase of nine days per decade since 1991.

1.4 On average, lakes and ponds across Vermont are icing-out one to three days earlier per decade since the 1970s and 1980s.

1.5 Extreme weather events such as droughts and floods are expected to continue to increase with climate change. Vermont experiences 2.4 more days of heavy precipitation than in the 1960s, most often in summer.

2 CLIMATE CHANGE IN FORESTS

2.1 Climate change is beginning to shift growing conditions for forests in Vermont, with greater changes expected to come, becoming more favorable for southern-adapted tree species and less favorable for currently adapted tree species. Species that will benefit from this change include northern red oak, shagbark hickory, and black cherry, while species including sugar maple, balsam fir, yellow birch, and black ash will be negatively impacted. While growing conditions will be significantly different by 2100, actual change in forest makeup will follow a delay as older trees die and are replaced by young ones.

2.2 Forest productivity, an important indicator of forest health and carbon storage, is amplified by a longer growing season and greater atmospheric carbon dioxide (CO2) and is expected to increase in Vermont in the next 50–100 years. However, productivity will be highly variable by species and will likely begin to decrease by the end of the century as high summer temperatures, drought, and soil nutrient loss outweigh benefits.

2.3 Climate change is expected to continue exacerbating the threats that invasive plants, insects, and diseases already pose to the health of Vermont's forests. These threats are compounded by other climate-related factors, such as worsening storms and increasingly irregular precipitation.

2.4 Warmer winters and wetter summers already limit active forest management by shortening the time frames that forest operations can take place. These negative climate impacts are projected to strengthen in the future, potentially leading to cascading negative effects on rural economies, forest product markets, and management for forest health and climate adaptation.

2.5 Land use change and parcelization, most commonly conversion of forests to residential or commercial use, is a persistent trend in Vermont, a major threat to forest health and productivity, and a contributor to climate change.

2.6 As climate change impacts forest ecosystem function, there is a need for management to increase forest adaptive capacity. Current methods to achieve increased adaptive capacity at the ecosystem level (retaining ecosystem function despite threats to individual tree species or forest types) include increasing forest structural complexity and enhancing compositional and functional diversity and redundancy.

2.7 Climate change impacts will be more severe for urban trees because of the effects of the built environment on temperature and water cycling, as well as additional stressors associated with urbanized areas like soil compaction, soil fertility, and pollution.

2.8 Urban trees will be increasingly important to humans because of the services they provide. While urbanized areas in Vermont make up less than 2% of the state's land area, they are home to nearly 243,000 people, 39% of the Vermont population. Because of the high population density and lower tree cover in urbanized areas, per-tree ecosystem services can be higher than in a forest setting. In addition to critical climate and ecosystem benefits provided by trees everywhere, urban trees mitigate the urban heat island effect through cooling and shading and reduce stormwater runoff from extreme rainfall events

3 WATER RESOURCES

3.1 Due to extreme variation in precipitation with our changing climate, periods of prolonged dry-spells and drought, coupled with higher water usage in snowmaking and agriculture could exacerbate low water availability.

3.2 Increases in overall precipitation, and extreme precipitation, have caused streamflows to rise since 1960. Climate change will further this pattern, although the overall increase in streamflow comes with disruptions in seasonal flows cycles.

3.3 Increases in heavy precipitation jeopardize water quality in Vermont. Storms produce large runoff events that contribute to erosion and nutrient loading. Combined with warm temperatures, this creates favorable conditions for cyanobacteria blooms.

3.4 Increased occurrence of high streamflows increase the risk of flooding that causes damages to many roads and crossing structures. Risk reduction requires addressing outdated and unfit structures.

3.5 Nature-based solutions are an effective, low-cost approach to climate change adaptation. River corridor, floodplain, and wetland protection dampen flood impacts and improve water quality along with green infrastructure.

4 FISH AND WILDLIFE IN VERMONT

4.1 As climate change worsens, 92 bird species of Vermont, including the iconic common loon and hermit thrush, are expected to disappear from the landscape within the next 25 years.

4.2 Increasing warming trends are expected to result in an increase in white-tailed deer population and a mirrored decrease in moose population, which may have long-term impacts on Vermont's forest composition. Managing social systems (e.g. hunting) to account for changing public tolerance and demand for deer may provide one avenue to minimize this risk if undertaken proactively.

4.3 As warming trends reduce the severity of winters, the subsequent warming waters will have adverse effects on lake and river systems, including increased risk for harmful algal blooms (HABs) and reduced overall biodiversity and health in lake ecosystems.

5 AGRICULTURE AND FOOD SYSTEMS

5.1 Vermont's climate is already changing in ways that benefit its agricultural system, including longer growing periods (freeze-free periods lengthened twenty-one days since early 1900s) and milder temperatures (annual average temperature increase of 2°F (1.1°C) since the 1990s), allowing farmers to experiment with new crops or practices not previously viable in Vermont.

5.2 The changing climate also brings agricultural setbacks, such as negative impacts on fruit-bearing species like apple trees that require a sufficient over-wintering period for success in the next growing season. The maple syrup industry is also at risk due to variations in winter temperatures.

5.3 Climate models predict tougher growing conditions due to greater variability in temperature and precipitation, including heavy precipitation and dry spells.

5.4 Vermont's average annual precipitation has increased 6.7 inches since the 1960s. Summer precipitation has increased most (additional 2.6 inches since 1960s) and is characterized by more heavy precipitation events (defined as more than one inch of precipitation in one day) (additional 1.0 day/year), although spring precipitation has also increased notably (additional 2.11 inches/year since 1960s, and 0.8 days/year with heavy precipitation). Spring precipitation accumulates in the soil and can make farm operations difficult. While precipitation during the growing season is trending upward, precipitation falls in fewer, more extreme events and is coupled with longer periods of no rain at times when crop water requirements are still high; thus, irrigation may become increasingly important.

5.5 At the Earth's surface, increasing concentrations of carbon dioxide may benefit yields in crops that utilize the C3 photosynthetic pathway (i.e., many of Vermont's forages) if conditions are otherwise ideal. Conversely, an increase in surface-level ozone concentrations may reduce crop productivity.

5.6 Extreme events are expected to increase. More periods of flooding and drought will lead to more crop damage or failure. Stormwater and irrigation infrastructure will be crucial in mitigating these effects.

5.7 Agriculture and food systems may play an important role in mitigating climate change, if mitigation provides financial opportunities, are distributed fairly and accurately, and are implemented with careful monitoring, reporting, and verification. Urban and suburban areas in Vermont have the potential to improve adaptation and mitigation of climate change by growing food closer to where it is consumed.

6 ENERGY

6.1 Vermont drivers have the highest average miles traveled per capita in the Northeast United States. Transportation is the largest source of greenhouse gas emissions in Vermont. Thermal energy use is a close second to the largest source of greenhouse gas emissions in Vermont, and the largest use of energy. Reducing energy use in these sectors by choosing more efficient vehicles, selecting heat sources with less emissions, and weatherizing homes will help Vermont meet its energy goals.

6.2 The electricity in Vermont has the lowest carbon intensity in the country. Electrifying transportation and thermal energy use will significantly reduce Vermont's carbon footprint.

6.3 In the short term, there is extra power line capacity to serve significantly more load in Vermont; however, some areas of Vermont have limited capacity to support further renewable energy generation. Areas where there is limited generation hosting capacity could be prioritized to shift local energy use to electricity to reduce congestion on local transmission lines. The priority in areas with extra generation hosting capacity can be two-fold: building new renewable generation and electrifying local energy use.

6.4 The storms that cause the most frequent power outages are expected to become more intense in the future, increasing the frequency of power outages, particularly in winter. Vermont can increase its energy resilience with distributed solar and storage, secondary heating systems (e.g., wood), and community buildings with resilient heating solutions.

7 RECREATION AND TOURISM

Winter

7.1 Downhill skiing, with the help of snowmaking, will likely remain largely viable in Vermont up until approximately 2050. By 2080, the Vermont ski season will be shortened by two weeks (under a low emissions scenario) or by a whole month (under a high emissions scenario), and some ski areas will remain viable.

7.2 Winter temperatures are increasing in Vermont, reducing the length of season for most snow sports.

7.3 February Median Flow, a measurement used by ski areas to collect water for snowmaking, has steadily increased across Vermont.

Summer

7.4 Summer recreation activities in Vermont will continue to be popular, with water-based activities likely to increase in interest as air temperatures rise. However, water quality issues will also become more prevalent.

7.5 Vermont may see an increase in summer "seasonal climate refugees" as the rise in temperatures nationwide draws visitors looking to escape extreme heat.

7.6 Vermont has the potential to increase tourism revenue via gastrotourism and agritourism as the growing seasons lengthen.

Fall/Spring

7.7 Transition seasons are becoming more important for tourism and recreation as Vermont is already experiencing warmer temperatures in fall and spring.
7.8 Trees, particularly sugar maples, are an important aspect of many fall/spring recreation activities (leaf peeping, maple syrup, apple picking), but may be negatively affected by warmer temperatures.
7.9 Fall and spring seasons offer new opportunities for lower-cost recreation and tourism opportunities that attract a wider range of potential visitors.

8 HUMAN HEALTH

8.1 Climate change affects human health by exacerbating existing health problems and amplifying conditions for new health problems.
8.2 Individuals who are children, over 65 years of age, of low socioeconomic status, Indigenous, or have previous health issues are more vulnerable to the health effects of climate change.
8.3 Warmer and more moist temperatures in Vermont are likely to create more habitat for disease-carrying ticks and mosquitoes.
8.4 Increases in the number and severity of natural disasters in Vermont will likely increase the risk of injury, illness, and death.
8.5 Climate change could affect the quality and safety of food and water, which could lead to increases in food and water-borne illnesses.
8.6 Decreases in air quality will exacerbate existing chronic diseases and decrease water quality.
8.7 Mental health is inextricably linked with environmental health. Impacts from climate change could contribute to mental health challenges.

9 COMMUNITY DEVELOPMENT

9.1 Flooding is the most likely natural disaster to occur in Vermont and should be accounted for in all community development and planning efforts in the state; however, extremes will become more common, so community development and planning efforts should also account for chronic hazards, such as drought.
9.2 Systems interconnections are essential to consider in community development and planning of future climate change scenarios, particularly in the context of disasters.
9.3 Vermont is expected to continue to have a favorable climate under future climate change projections, however, there is very little information to predict if the state will face an influx of climate migration.

9.4 Engaging in planning is essential for Vermont communities to access federal funding and to prepare for current and future climate change impacts, including population growth, flooding, and droughts.

9.5 Climate change will not impact all communities equally; the needs and capacity of vulnerable populations should be considered with all community planning efforts.

10 SPECIAL TOPIC: CARBON SEQUESTRATION IN AGRICULTURAL SOILS

10.1 The soil carbon sequestration potential of agricultural management practices in Vermont is uncertain and likely mediated by site-specific factors such as soil type, geography, land use history, and weather. Climate change mitigation benefits are possible but not guaranteed from the use of common practices implemented to sequester carbon (such as cover cropping, conservation tillage, no-till, and rotational grazing) on Vermont agricultural lands. There is evidence, however, that these practices can improve soil health and increase farm resilience to climate change.

10.2 Assigning carbon offsets or payments for climate mitigation services provided by Vermont agricultural lands based on practice adoption alone currently lacks a strong scientific foundation. Further investigation and monitoring is needed to improve understanding of management practices and soil carbon sequestration, including field studies and modeling. Well-calibrated models, validated for application in Vermont, have potential for identifying relationships between management change(s) and carbon dynamics. Participatory research that engages the expertise and needs of farmers is necessary to assess the local impacts of best management practices and make projections into the future.

10.3 Whole-system accounting is required to assess potential trade-offs and to determine net climate change mitigation benefits of soil management strategies. Changes in soil carbon stocks at a given location are only one piece in climate mitigation accounting. In all cases where offsite carbon sources are being used to boost soil organic carbon, a broader life cycle assessment extending beyond the farm gate is needed that considers offsite carbon source removal, transport, and processing; alternative end uses of the carbon source; interactions with other soil GHG-producing processes; and synergies between the soil amendments and the input of in situ plant-derived carbon. It is critical to keep in mind the primary objective: increase the net transfer of CO2-equivalents from atmosphere to land – only strategies achieving this primary objective should be considered climate mitigation. Failing to account for other fluxes of carbon and greenhouse gases could result in unintended consequences due to trade-offs.

ACRONYMS

ASCE • American Society of Civil Engineers

BRIC • Building Resilient Infrastructure and Communities (FEMA)

C • Carbon

CARES • Coronavirus Aid, Relief, and Economic Security Act (U.S.)

CDC • U.S. Centers for Disease Control and Prevention

CEP • Comprehensive Energy Plan (Vermont)

CFS • Cubic feet per second

CH4 • Methane

CIS • Community Information Systems (FEMA)

CO2 • Carbon dioxide

COPD • Chronic obstructive pulmonary disease

DEIJ • Diversity, equity, inclusion, and justice

EAB • Emerald ash borer

ED • Emergency department

EEE • Eastern Equine Encephalitis (mosquito-borne disease)

EPA • U.S. Environmental Protection Agency

EV • Electric vehicles

FEMA • U.S. Federal Emergency Management Agency

FMF • February median flow

FTC • Forest tent caterpillar

GCM • Global climate model

GHGs • Greenhouse gases

GI • Green infrastructure

GWSA • Global Warming Solutions Act (Vermont)

HAB • Harmful algal bloom

HWA • Hemlock Wooly Adelgid

IPCC • Intergovernmental Panel on Climate Change

LCA • Life cycle assessment

LOI • Loss on ignition

Mgal • Million gallons (of water)

MMt CO2e • Million metric tons of carbon dioxide equivalent

MSPR • Multi-species pastured rotation

Mt CO2e • Metric tons of carbon dioxide equivalent

N2O • Nitrous oxide

NASS • National Agricultural Statistics Service

NFIP • National Flood Insurance Program

NFNA • New Farms for New Americans

NIOSH • National Institute for Occupational Safety and Health

NOAA • National Oceanic and Atmospheric Administration

NPP • Net primary productivity

NWS • National Weather Service

O3 • Ozone

PES • Payment for ecosystem services

RCP • Representative concentration pathway

RECs • Renewable energy certificates

SFHA • Special Flood Hazard Area (FEMA)

SOC • Soil organic carbon

SPEED • Sustainably Priced Energy for Economic Development (Vermont)

T&D • Transmission and distribution

TNC • The Nature Conservancy

TRPT • Transportation Resilience Planning Tool (Vermont)

UNFCCC • United Nations Framework Convention on Climate Change

USDA • U.S. Department of Agriculture

USGS • United States Geological Survey

VCA • Vermont Climate Assessment

VCE • Vermont Center for Ecostudies

VCRD • Vermont Council on Rural Development

VDH • Vermont Department of Health

VELCO • Vermont Electric Power Company

VNRC • Vermont Natural Resources Council

VOREC • Vermont Outdoor Recreation Economic Collaborative

VT PUC • Vermont Public Utility Commission

VT UCF • Vermont Urban & Community Forestry Program

WNV • West Nile Virus (mosquito-borne disease)

TABLE OF CONTENTS

1 CLIMATE CHANGE IN VERMONT

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1.1 KEY MESSAGES

1. Vermont's annual average temperature has increased by almost 2°F (1.11°C) since 1900. Winter temperatures have increased 2.5 times faster than annual temperatures over the past sixty years, and the number of very cold nights has decreased by over seven days in the same time period.
2. Average annual precipitation in Vermont has increased by 21% since 1900 and has become more variable in the last decade. Annual snowfall has been decreasing since the 1960s, yet winter precipitation has increased, suggesting that more winter precipitation is falling as rain.
3. Vermont's freeze-free period has lengthened by three weeks since 1960; the trend has accelerated to an increase of nine days per decade since 1991.
4. On average, lakes and ponds across Vermont are icing-out one to three days earlier per decade since the 1970s and 1980s.
5. Extreme weather events such as droughts and floods are expected to continue to increase with climate change. Vermont experiences 2.4 more days of heavy precipitation than in the 1960s, most often in summer.

1.2 BACKGROUND AND GLOBAL CONTEXT

The world's climate is changing and is projected to continue to change over the next century. This chapter examines recent trends in our local climate and can help us understand how climate change will continue to affect Vermont.

1.2.1 Weather and Climate

How does climate differ from weather? Climate is the average weather (defined over 30-year averaging periods by the National Oceanic and Atmospheric Administration—NOAA) experienced in a place (e.g., you expect cold and snow in Vermont's winters), while weather is the day-to-day variation in things like temperature and precipitation (e.g., the 10-day forecast).

There is a saying that “climate is what you expect, weather is what you get”. Unfortunately, as the climate changes, it is getting increasingly difficult to know what to expect.

1.2.2 Causes of Climate Change

Climate change is largely caused by increasing heat trapped in the Earth’s atmosphere. The release of heat-trapping greenhouse gases, particularly carbon dioxide (CO_2), has increased the heat in the atmosphere. Greenhouse gases act like a transparent blanket around the Earth—allowing sunlight to reach and warm the air, ground, and oceans but preventing heat from leaving the atmosphere into space. Over time, the trapped heat accumulates, warming our planet and causing temperatures to rise. Although greenhouse gases are a natural part of the atmosphere, human activities such as burning fossil fuels have drastically increased their abundance (Hayhoe et al. 2018). Like adding an extra blanket, the effect is to warm the Earth beyond the temperature variability expected based solely on natural forcings (e.g., variability of the Earth’s orbit, volcanic eruptions). Oceans absorb roughly 90% of the excess heat, but humans are starting to feel the remaining 10%, as the atmosphere warms the land.

Human activities have been releasing greenhouse gases since the beginning of the Industrial Revolution in the mid-1700s. Human sources of greenhouse gases increased dramatically in the mid-20th century as burning of fossil fuels increased. Human contributions to greenhouse gas emissions, and thus global temperature change, exceed any variations in natural factors such as the Earth’s orbit, volcanic activity, or energy emitted by the Sun (Hayhoe et al. 2018). Further, the rate of human-induced greenhouse gas emissions has increased far faster than forests, oceans, and other natural processes can remove them from the atmosphere.

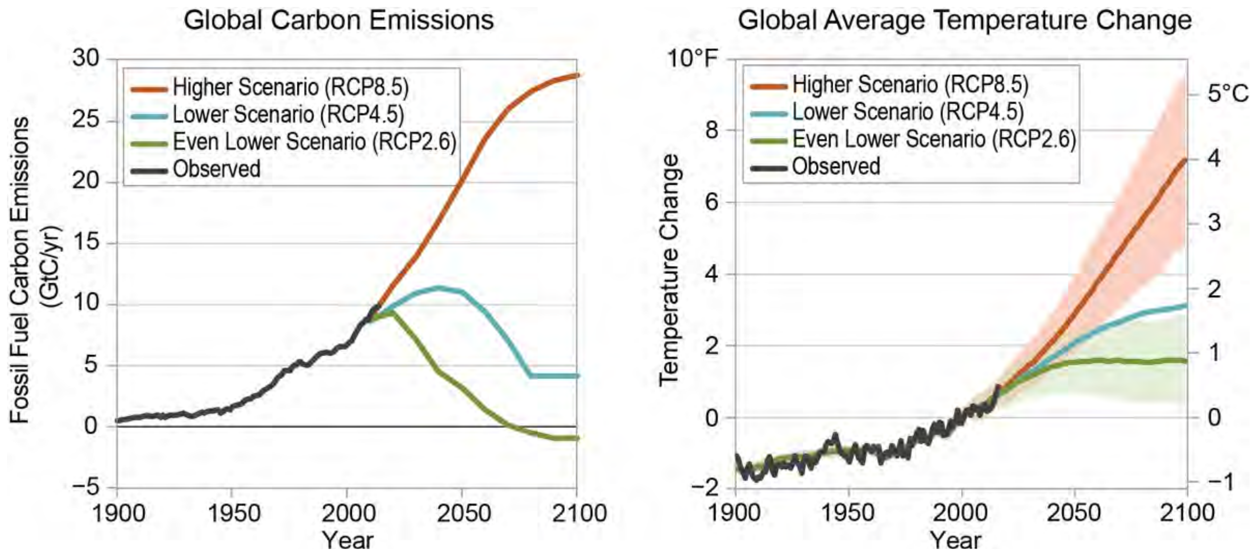

Figure 1-1: Historical and projected global carbon emissions (left); historical and projected global temperature change with global climate models' range shaded in red and green (right), 1900 to 2100 (Hayhoe et al. 2018)

1.2.3 Future Climate Change

Scientists have developed scenarios that represent plausible alternative futures based on key drivers and relationships between greenhouse gas emissions and climate change mitigation actions. Scenarios are neither forecasts nor projections, but they are useful in considering which pathway(s) humans may pursue. The Intergovernmental Panel on Climate Change (IPCC), a body of the United Nations, provides global scientific analysis on climate change and defines future climate change scenarios based on four representative concentration pathways (RCPs). Each RCP corresponds to an increase in radiative forcing, or change in energy flux in the atmosphere caused by climate change by the year 2100 based on a particular scenario. RCP2.6, the most stringent mitigation scenario, has peak radiative forcing at 3 W m^{-2} before 2100 and then declines. The intermediate scenarios, RCP4.5 and RCP6.0, stabilize radiative forcing at 4.5 W m^{-2} and 6.0 W m^{-2} after 2100, respectively. The RCP with the highest amount of climate change, RCP8.5, has the highest radiative forcing of 8.5 W m^{-2} by 2100, which continues to rise after that time. RCP8.5 estimates a global increase in temperature of 3.7

degrees C, 0.63 meters sea level rise, more extreme weather events, and requires high levels of societal adaptation at a high cost by 2100 (Table 1-1; Figure 1-1; IPCC 2014).

Table 1-1: Description of RCP pathways used in CMIP5 Global Climate Model, adapted from IPCC Summary for Policymakers (IPCC 2014)

	Global mean surface temperature change (ºC) *Mean [likely range]*		**Global mean sea level rise (m)** *Mean [likely range]*	
Scenario	2046–2065	2081–2100	2046–2065	2081–2100
RCP2.6	1.0 *[0.4 to 1.6]*	1.0 *[0.3 to 1.7]*	0.24 *[0.17 to 0.32]*	0.40 *[0.26 to 0.55]*
RCP4.5	1.4 *[0.9 to 2.0]*	1.8 *[1.1 to 2.6]*	0.26 *[0.19 to 0.33]*	0.47 *[0.32 to 0.63]*
RCP6.0	1.3 *[0.8 to 1.8]*	2.2 *[1.4 to 3.1]*	0.25 *[0.18 to 0.32]*	0.48 *[0.33 to 0.63]*
RCP8.5	2.0 *[1.4 to 2.6]*	3.7 *[2.6 to 4.8]*	0.30 *[0.22 to 0.38]*	0.63 *[0.45 to 0.82]*

Scientists estimate the impacts of altered atmospheric composition on the climate using global climate models (GCMs). Complex computer models, GCMs simulate how the atmosphere interacts with the oceans and landscape to understand how temperatures, precipitation, and weather patterns may change over time. Each GCM performs slightly differently, e.g., a GCM developed in Europe may more closely match the observed climate in that region compared to other regions. Typically, a large number of GCMs are run with the same scenarios, and together they predict the future climate associated with each scenario, e.g., the shaded cone in Figure 1-1 shows a range of GCM estimates.

In Vermont and across the world, the climate is changing and will continue to change over the next century. The Earth has warmed by 1.8°F since 1901 and could warm by another 3.6°F to 9°F by 2100, depending on human activities (Hayhoe et al. 2018).

1.2.4 Signs of Climate Change

Different parts of the world experience climate change differently. Warm air has the capacity to hold more moisture than cooler air. As the atmosphere's temperature rises, evaporation and humidity increase. Eventually, this water vapor is released as precipitation, effectively increasing rainfall potential in some areas, even as this heat and evaporation cause other regions to suffer more droughts. The high energy in warmer and wetter air can lead to more intense storms, even hurricanes, and increases the potential for more destructive winds and heavier downpours (Dupigny-Giroux et al. 2018; Hayhoe et al. 2018). Climate-related changes in the atmosphere's energy are increasing the variability in weather due to the stalling of weather patterns and a changing climate baseline. Increased variability means places like Vermont might experience both more frequent dry-spells or drought and more intense rainstorms (Betts 2017).

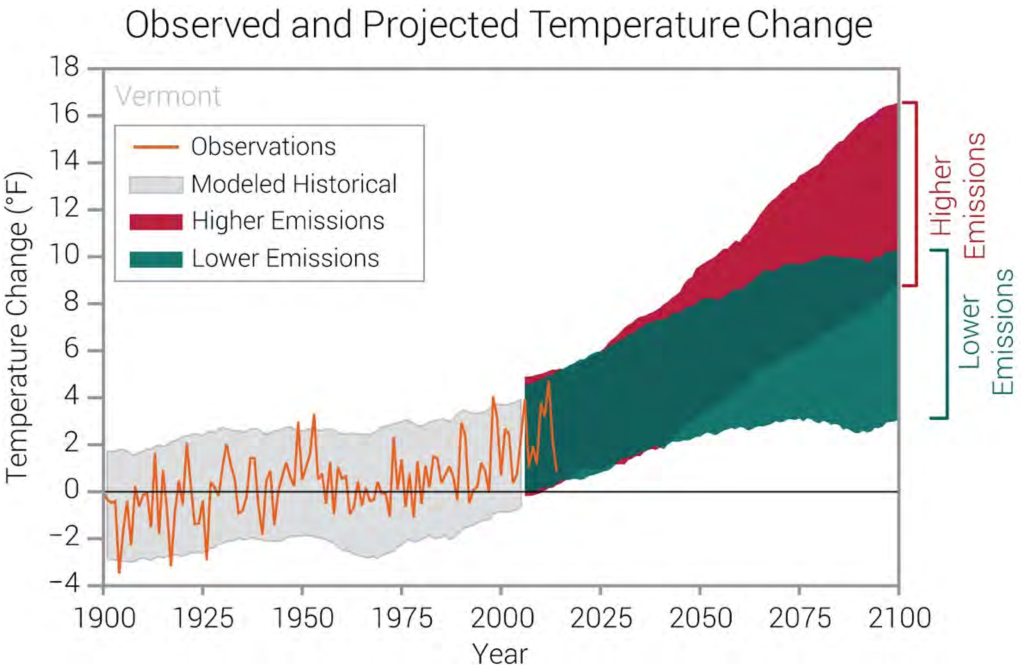

Figure 1-2: Observed and projected temperature rise for the state of Vermont, 1900 to 2100 (Runkle et al., 2017, Fig. 1)

1.2.5 Vermont's Future Climate

Vermont's climate is projected to warm faster than the global average. Vermont's temperature may warm by 5°F to 9°F, or more, by 2100 depending on the emissions scenario (Betts 2017; Figure 1.2). Rising temperatures will increase the freeze-free growing season in the Northeast by two-to-three weeks by the middle of this century (Dupigny-Giroux et al. 2018). As ice and snow melt earlier in the spring, longer and warmer summers could lead to more evaporation, which could favor more frequent summer droughts (Betts 2017).

At the same time, the total amount and intensity of precipitation is expected to increase, particularly in winter and spring (Betts 2017). Across the Northeast, monthly precipitation for December through April is projected to increase by up to one inch by 2100 in RCP8.5, the IPCC's highest emissions scenario (Dupigny-Giroux et al. 2018). The Northeast is also expected to experience more frequent and powerful storms (Dupigny-Giroux et al. 2018). Factors like wetter winters and springs, a faster spring thaw, and more intense rainfall could contribute to increased flooding across Vermont. Intense rainfall can be particularly hazardous when it falls on soils that are already waterlogged, as was the case with Hurricane Irene in 2011.

1.3 VERMONT'S CHANGING CLIMATE (METHODS)

In Vermont, recent decades have seen warmer temperatures, increased precipitation, earlier spring thaws, and a longer growing season. Climate models give useful projections of the climate for large regions like the entire Northeast, but they can't always capture variations in climate at finer resolutions, such as within Vermont. Historical climate records document local trends and changes in climate within Vermont. Recent trends are likely to continue for the next few decades, so long-term climate observations from 18 weather stations around Vermont are used in this analysis.

This analysis of Vermont's changing climate covers temperature trends; precipitation trends, including heavy precipitation and snowfall; climate indicators, including the length of the freeze-free period and the timing of ice-out; and extreme events such as flooding and droughts.

1.3.1 Historical Climate Data

Our analyses utilized observations from 18 National Oceanic and Atmospheric Administration National Weather Service (NOAA NWS) U.S. Cooperative Observer Network weather stations across Vermont (Figure 1-3; see Table 1A-1 for station attributes). Data was acquired from the Global Summaries of the Month, Version 1 Dataset (Lawrimore et al. 2016) and from the Applied Climate Information System (DeGaetano et al. 2015; xmACIS 2021). These eighteen stations were selected because they have at least thirty years of observations with which we could compute yearly and seasonal climate variables. All climate variables were calculated for the state of Vermont and for each of its three climate divisions (northeastern, western, and southeastern). Climate divisions were defined by the U.S. Weather Bureau (now National Weather Service) and represent regions of a state that have a similar climate, similar dominant crop types, or are within the same drainage basin, and they are useful for local climate applications (Figure 1-3; Guttman and Quayle 1995).

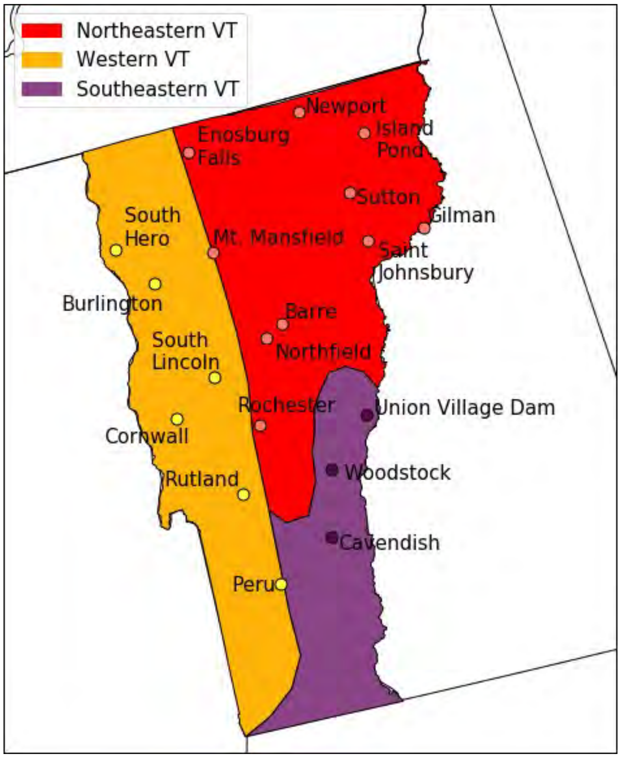

Figure 1-3: Locations of the 18 stations (points) and climate divisions utilized in this analysis

Climate variables were calculated for each year and season, but not all stations have complete records for each year or season. Station data were used for annual analyses when there were more than ten months of good observations. (A month of good observations is defined as missing no more than five days of observations.) Otherwise, annual analyses were not calculated for that station. Station data were used for seasonal analyses if all three months in the season had good observations (again, defined as missing no more than five days per month). Seasons were defined meteorologically as follows: winter: December, January, and February (DJF), spring: March, April, and May (MAM), summer: June, July, and August (JJA), and fall: September, October, and November (SON). Annual and seasonal average values for the state were calculated as the average of annual or seasonal climate variables for all active stations with good observations; likewise, climate division average values utilized good observations within the climate division in question. Decadal mean values for the state and climate divisions were computed by averaging that decade’s annual values for all stations across the state or climate division.

As new stations came online over time, and some years or seasons were discarded for lack of good observations, the number of stations considered each year varied (Figure 1A-1). Sensitivity tests were completed to address possible impacts that the variable number of stations may pose to the following results. Representative stations were chosen as the station with the longest complete record in a climate division and were not subject to station relocation. The representative stations’ trend and decadal variability analyses were compared to analyses for the climate division. Results from sensitivity testing illustrated consistency in the magnitude and direction of trends and decadal variability between individual stations and their climate division over all time periods considered. The changing number of stations over time does not appear to impact findings. The annual standard deviation around the long-term (1900–2020) mean temperature does increase as the Mount Mansfield station comes online in 1955, but the inclusion of this station does not appear to have an impact on the magnitude of trends or decadal variability.

1.3.2 Notes on Snowfall Data

Measurements of snowfall are inherently difficult to capture due to blowing snow, measurements consistency, and varying water content in snow. Information presented here on snowfall trends and variability in snowfall started in 1930 because Vermont’s first snowfall measurements in more than one climate division began in 1930, although snowfall measurements did not start in southeastern Vermont until 1946. Snowfall is reported in inches of snow. Seasonal precipitation, including snow and rain, is reported as “liquid equivalent”, i.e., the amount of liquid produced if you were to melt frozen precipitation. Liquid equivalent precipitation measurements ensure that frozen precipitation (i.e., snow) with different water content can be directly compared. The average snow-to-liquid ratio in Vermont is 12:1 to 13:1 (Baxter et al. 2005), meaning that melting the twelve to thirteen inches of snow on the ground would produce one inch of liquid water. The snow-to-liquid ratio is highly variable across Vermont and can range more than seven inches above or below the average, the largest being 40:1 or greater (P. Banacos, personal communication, 2021). The lowest snow-to-liquid ratios (wettest snows) across the state are in southeastern Vermont due to the proximity to the Atlantic Ocean, and the highest snow-to-liquid ratios (driest snows) are in the northern portions of the western and northeastern climate divisions of Vermont (Baxter et al. 2005).

1.3.3 Statistical Analyses

Trends in climate variables were computed using the Mann-Kendall test (Kendall 1975; Mann 1945) and were evaluated for statistical significance using the pyMannKendall package in python (Hussain and Mahmud 2019). A statistically significant trend is unlikely to have occurred randomly, and so is likely a meaningful trend. Trends which are not statistically significant are unlikely to be meaningful.

1.3.4 Climate Normals

NOAA NWS considers climate the most recent thirty years of observed weather patterns and calls this climate normals. Climate normals are used daily for weather interpretation, as they help forecasters explain how current weather conditions compare to the recent past described by the climate normal. NOAA climate normals are updated every ten years in accordance with standards set by the World Meteorological Organization and an 1890 congressional mandate (National Centers for Environmental Information 2021). NOAA NWS updated climate normals in spring 2021. For Vermont, these updated values highlighted the impacts of climate change. For example, from the 1981-2010 climate normal to the 1991-2020 climate normal, the average time from Burlington’s first to last frost decreased by 6 days (shorter winter) and the average annual temperature increased from 46°F to 47.6°F (xmACIS 2021; analysis by Peter Banacos, NOAA NWS Burlington).

In this study, change in climate and long-term trends were considered for three periods: 1) near-term (1991 to 2020), consistent with the calculation of NOAA Climate Normals, 2) mid-term (1960 to 2020), and 3) long-term (1900 to 2020). The number of active stations with good observations for each time-period are shown in Figure 1A-1.

1.4 VERMONT’S RISING TEMPERATURES

Historical observations indicate Vermont’s temperatures are increasing based on near-, mid-, and long-term trends and individual seasons. A comparison of the long-term (1900-2020), mid-term (1960-2020), and near-term (1991-2020) climate periods shows accelerating rates of warming for all temperature variables—average, seasonal (except winter), minimum, and maximum temperatures (Table 1-2).

1.4.1 Average Temperatures

Vermont’s average annual temperature has increased by 2°F (42.1°F to 44.1°F) in the long-term, most of which occurred more recently: 2°F (42.6°F to 44.1°F) in the mid-term and 1.1°F (43.0°F to 44.1°F) in the near-term (Table 1A-2).

1.4.2 Seasonal Temperature Changes

In the long-term, average temperature has increased since the early 1900s the most in winter (+3.3ºF), least in spring (+0.2ºF), and in between in summer and fall (+1.6ºF and +1.5ºF respectively; Table 1-2). Compared to the long-term mean winter temperature (1900–2020) of 19.1ºF, winter temperatures vary by +/- 0.9ºF, compared to a +/-0.6ºF variation in summer temperatures (Figure 1-5).

In the mid-term (1960–2020), average winter temperatures have warmed 2.3 and 2.8 times faster than summer and fall, respectively. Warming during this period was greatest with observed minimum temperatures: average minimum temperatures increased +3ºF, 2.6 times faster than average maximum temperatures (+1ºF) (Table 1A-3). Southeastern Vermont had the largest increase in winter minimum temperatures, warming 0.6ºF/decade since 1960 compared to 0.5ºF/decade for northeastern Vermont (Northeast Kingdom), and 0.2ºF/decade for western Vermont (Champlain Valley; not shown). From1991 to 2020, winter temperatures have increased from 19.8ºF to 20.7ºF (Table 1A-2).

Table 1-2: Trend and total change in temperature variables are computed on annual averages using available data for each year for all stations.

	Trend (per decade)			Total change		
	1900–2020	1960–2020	1991–2020	Since 1900	Since 1960	Since 1991
Annual Avg. Temperature (°F)	+0.04	+0.26*	+0.52	+1.95	+1.47	+1.04
Winter (DJF)	+0.12	+0.66*	+0.54	+3.35	+3.08	+0.90
Spring (MAM)	−0.03	+0.10	+0.15	+0.15	+0.94	+0.31
Summer (JJA)	+0.03	+0.29*	+0.42	+1.45	+1.84	+0.92
Fall (SON)	−0.001	+0.23*	+0.75*	+1.59	+1.04	+1.80
Avg. Max. T. (°F)	−0.06	+0.18*	+0.51	+1.06	+1.04	+0.84
Avg. Min. T. (°F)	+0.15*	+0.47*	+0.70*	+2.79	+2.63	+1.33
Days with max. T. > 90°F	−0.01	+0.11	+0.48	+1.49	+1.19	+1.32
Days with min. T. > 70°F	+0.04*	+0.20*	+0.48*	+1.14	+1.51	+1.15
Days with max. T. < 0°F	−0.63*	−2.08*	−3.04	−10.81	−10.01	−3.97
Winter days w/ max. T. > 50°F	+0.12*	+0.31*	−0.04	+1.85	+1.82	−0.17

Key:

< -5	-5 – -2	-2 – -0.5	-0.5 – 0	0 – 0.5	0.5 – 2	2 – 5	> 5

Note: Trend values (°F/decade or days/decade) that are bolded and noted by an asterisk are statistically significant to 95% confidence. Total change since 1900 is the difference between the 1900–1909 and 2011–2020 averages, total change since 1960 is the difference between the 1960–1969 and 2011–2020 averages, and total change since 1991 is the difference between the 1991–2000 and 2011–2020 averages. There is no estimate of significance for the total change values. Cells in the table are color-coded based on their value using the key below.

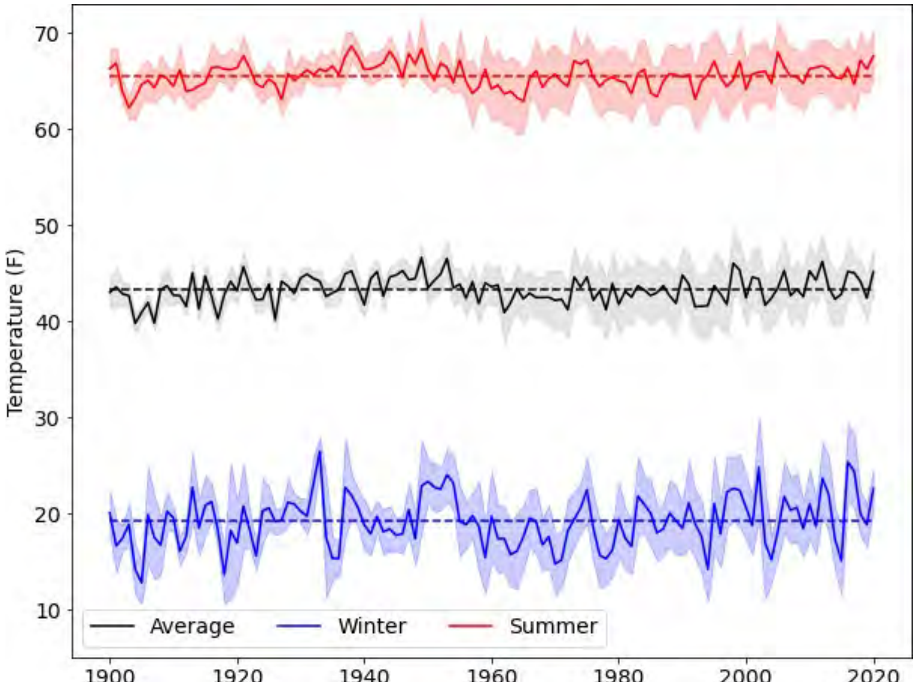

Figure 1-5: Annual temperatures by year: annual average (black line), winter months (DJF; blue line), and summer months (JJA; red line).

Note: Dashed lines indicate the long-term (1900–2020) mean. Shading represents the standard deviation of all observations. Increased standard deviations after 1955 can be attributed to the Mount Mansfield station coming online.

Winter warming across Vermont is reflected in the coldest nights and warmest winter days. The number of very cold nights (minimum temperature below 0°F) has decreased, and the largest changes have been in recent decades: there have been 0.6 fewer very cold nights per decade since 1900, two fewer very cold nights/decade since 1960, and three fewer very cold nights/decade since 1991 (Table 1-2; Figure 1-7). Southeastern Vermont has experienced the largest decreasing trend in the number of very cold nights: 2.8 days/decade since 1960 (not shown). On the other hand, warm winter days (maximum temperatures above 50°F) have increased by almost two days since the early 1900s and by the same amount since 1960 across the state of Vermont (Table 1-1; Figures 1-6 and 1-7).

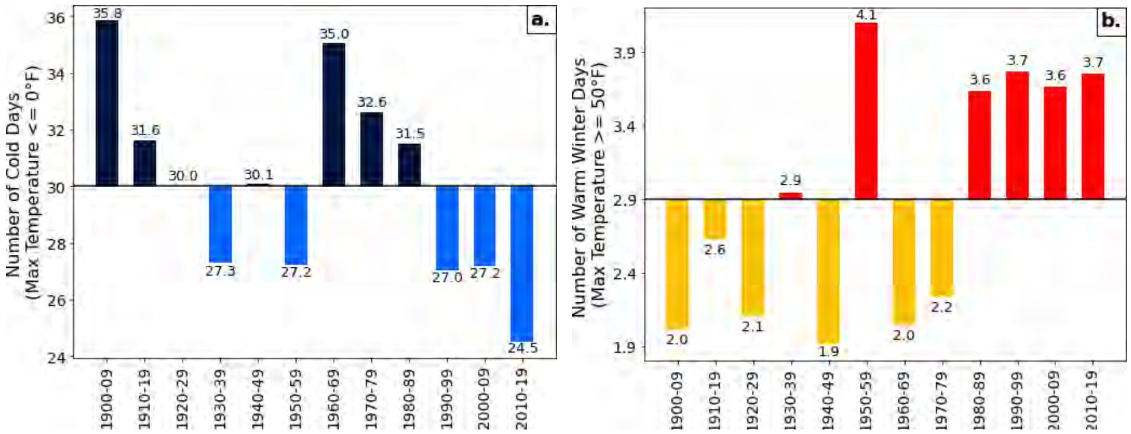

Figure 1-6: Decadal averages of cold and warm winter days plotted above and below the 1900–2019 mean value (solid black line).

Note: (a) The number of days with minimum temperature below 0°F. (b) The number of winter days with maximum temperature above 50°F.

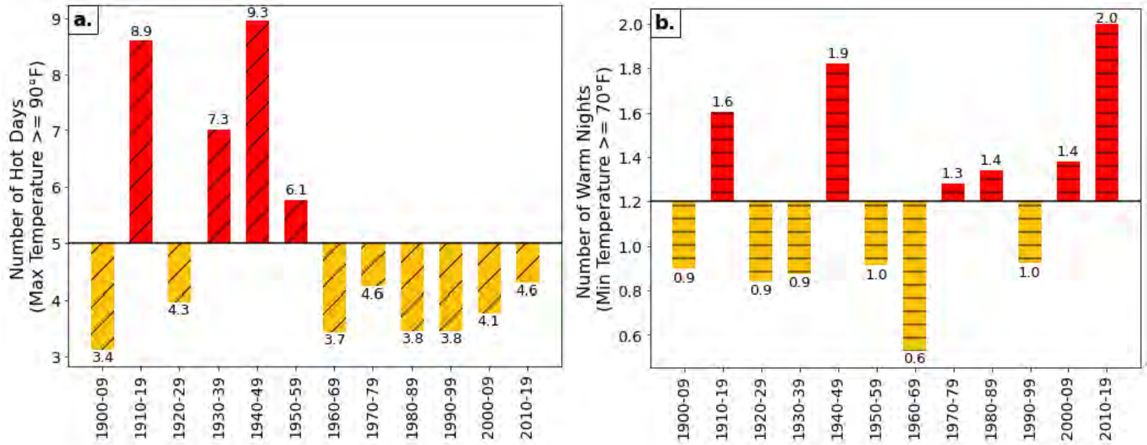

Figure 1-7: Decadal averages of hot days and warm nights plotted above and below the 1900–2019 mean value (solid black line)

Note: (a) Number of days with maximum temperature above 90°F (diagonal hash marks) and (b) Number of days with minimum temperature above 70°F (horizontal hash marks).

1.5 INCREASING PRECIPITATION

1.5.1 Average Annual Precipitation

Average annual precipitation in Vermont increased by 21% (7.5 inches) between the early 1900s and 2020, averaging an increase of 1.4 inches per decade since 1960 (Figure 1-8, Table 1-3). Precipitation increases span the four seasons. GCMs project that the Northeast will experience the greatest precipitation rise in winter and spring, yet so far Vermont has experienced the greatest precipitation increase in summer: 2.5 inches since the early 1900s (Table 1-3). Both spring and fall precipitation have increased by 2.4 inches, while winter precipitation has increased by 1.5 inches (Table 1-3). Trends since 1960 also show summer precipitation increasing at the fastest rate, (0.5 inches per decade), while winter and fall precipitation both have increased at similar rates of 0.3 inches per decade. Spring precipitation has increased the slowest, at a rate of 0.2 inches per decade (Table 1-3; Table 1A-3).

Northeastern Vermont has experienced the largest increase in annual precipitation since the early 1900s (26% increase, 9.1 inches), followed by western Vermont (23% increase, 7.3 inches). Southeastern Vermont had the smallest increase (16%, 5.9 inches). Related, average annual precipitation increased twice as fast in northeastern Vermont as in southeastern Vermont (1.2 inches per decade since 1900 in northeastern Vermont as compared to 0.6 inches per decade (0.9 inches per decade in western Vermont; not shown). Precipitation increased slightly faster in higher elevations (stations over 1000 ft) than in lower elevations (1.4 inches per decade since 1960 as compared to 1.2 inches per decade; Regional data available upon request.)

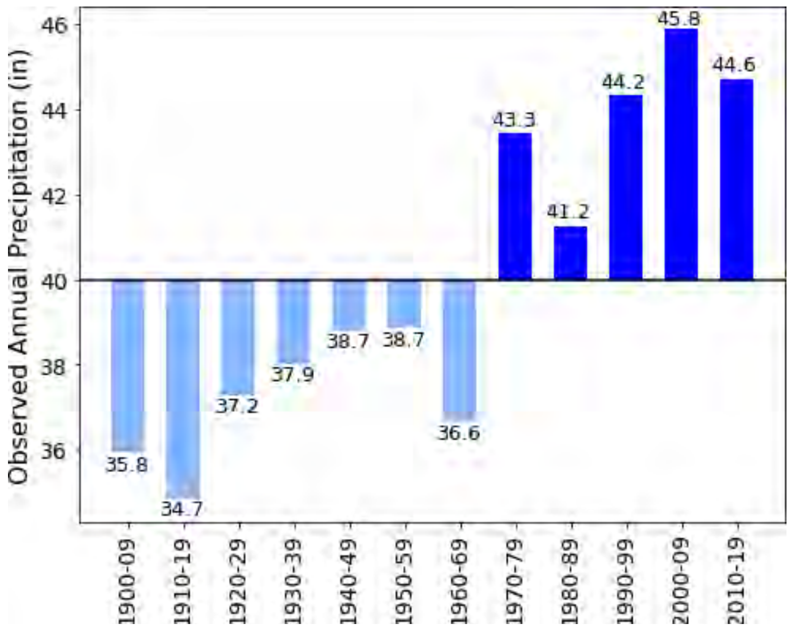

Figure 1-8: Decadal averages of observed annual precipitation in Verm

Table 1-3: Trend and total changes in precipitation.

	Trend (per decade)			Total change		
	1900–2020	**1960–2020**	**1991–2020**	**Since 1900**	**Since 1960**	**Since 1991**
Total precipitation (in)						
Annual	+0.90*	+1.38*	+0.21	+7.46	+6.71	−0.65
Winter (DJF)	+0.21*	+0.30*	+0.25	+1.49	+1.77	−0.01
Spring (MAM)	+0.19*	+0.21	−0.02	+2.36	+2.11	+0.38
Summer (JJA)	+0.28*	+0.50*	+0.61	+2.46	+2.59	+0.80
Fall (SON)	+0.25*	+0.34	−0.40	+2.44	+2.44	−0.74
Days with precipitation above 1 inch (days)						
Annual	+0.26*	+0.49*	+0.13	+1.99	+2.39	+0.13
Winter (DJF)	+0.05*	+0.08	+0.07	+0.004	+0.36	−0.13
Spring (MAM)	+0.06*	+0.11*	+0.03	+0.58	+0.76	+0.13
Summer (JJA)	+0.12*	+0.20*	+0.34	+1.22	+1.03	+0.44
Fall (SON)	+0.05*	+0.11	−0.09	+0.48	+0.48	−0.12

Key:

< -0.5	-0.5– 0	0–0.5	0.5–2	2–5	>5

Note: Variables are computed with annual averages using available data for each year. Trend values represent change per decade and those that are bolded and noted by an asterisk (*) are statistically significant to 95% confidence. Total change since 1900 is the difference between the 1900–1909 and 2011–2020 averages, total change since 1960 is the difference between the 1960–1969 and 2011–2020 averages, and total change since 1991 is the difference between the 1991–2000 and 2011–2020 averages. There is no estimate of significance for the total change values. Cells in the table are color-coded based on their value using the key above.

1.5.2 Heavy Precipitation

Heavy precipitation events, defined as more than one inch of precipitation in a day, have grown at a rate of 0.26 days per decade since the early 1900s and 0.5 days per decade since the 1960s (Figure 1-8; Table 1-3). Most of the total increase in the number of heavy precipitation days since the early 1900s has occurred in summer (1.2 days of the total near 2 day increase in the number of annual heavy precipitation days since the early 1900s). Heavy precipitation days have increased by 0.6 and 0.5 days since the early 1900s for spring and fall respectively, and by close to zero days for winter. Since 1960, heavy precipitation days have increased about twice as fast in summer than in other seasons (Table 1.2).

Increased summer precipitation and heavy precipitation events could be due, in part, to an increase in summer thunderstorms, which may be missed in GCMs. Large winter storm systems (e.g., nor'easters) can cover entire states, but thunderstorms are much smaller (10 km). On the other hand, GCMs operate at much larger scales and don't include the fine-scale dynamics necessary to account for thunderstorms. As a result, it is possible that precipitation projections for the Northeast do not account for the portion of summer precipitation increase that would be due to smaller-scale storm systems like thunderstorms. Local observations of climate also allow for a more in-depth understanding of changing precipitation patterns (in both time and space) within the state of Vermont.

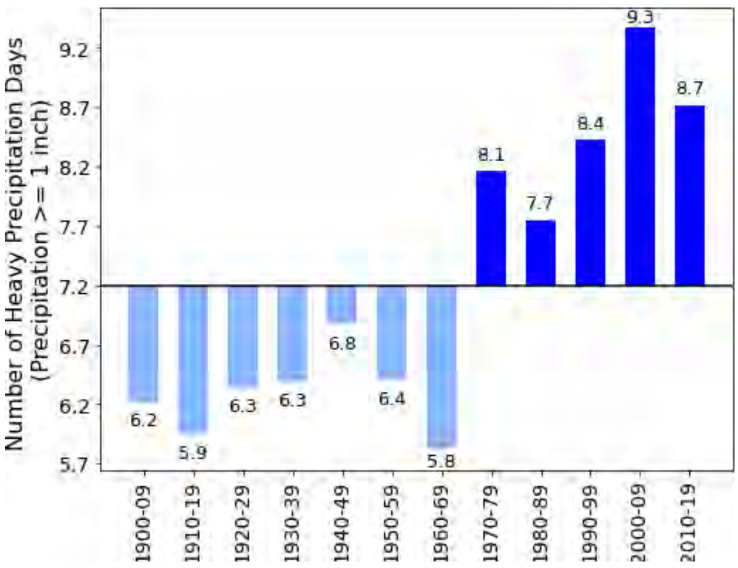

Figure 1-9: Decadal averages of the observed number of days per year with heavy precipitation in Vermont

Note: Heavy precipitation events are defined as more than one inch of precipitation. Decadal average values are plotted above and below the 1900–2019 mean value (solid black line). This data is computed for the state of Vermont based on available data for each decade

1.5.3 Snowfall

Average annual snowfall in Vermont increased as precipitation increased over the last century, but snowfall peaked between 1965 and 1979 (a particularly cold period) and has been highly variable since, with some decades reaching eight-to-ten inches above average (Figure 1-9; Table 1-4). Average annual snowfall has increased from an average of 68 inches in 1930–1939 to an average of 86 inches in 2011–2020 (an 18-inch increase), but snowfall has decreased by 10 inches relative to 1960–1969 (which averaged 96 inches; Tables 1-4 and 1A-4). However, this decline in snowfall since the 1960s has occurred at the same time that total winter precipitation has increased, suggesting that the decrease in snowfall is due to warming temperatures rather than drier winters, and that a greater portion of winter precipitation is falling as rain rather than snow.

The greatest increase in annual snowfall (and smallest subsequent decrease) was in northeastern Vermont, where average annual snowfall was 24 inches higher in the 2010–2019 than in 1930–1939 (Table 1-4). The region of northeastern Vermont has experienced the largest increase in annual precipitation and, on average, the coldest temperatures.

All regions of Vermont have experienced declines in snowfall since the 1960s, a time with high snowfall relative to the mean from 1930–2020 (Figure 1-9). Southeastern and western Vermont experienced greater declines in snowfall relative to the 1960s compared to northeastern Vermont (Table 1-4). These trends indicate that as the climate continues to warm, annual snowfall is likely to continue to decline because more winter and spring precipitation will fall as rain. Although average annual snowfall is declining, annual snowfall, much like Vermont's winter temperatures, remains highly variable from year to year. Therefore, while Vermont's winters may become milder and less snowy on average, any given year could be quite snowy (Betts 2017).

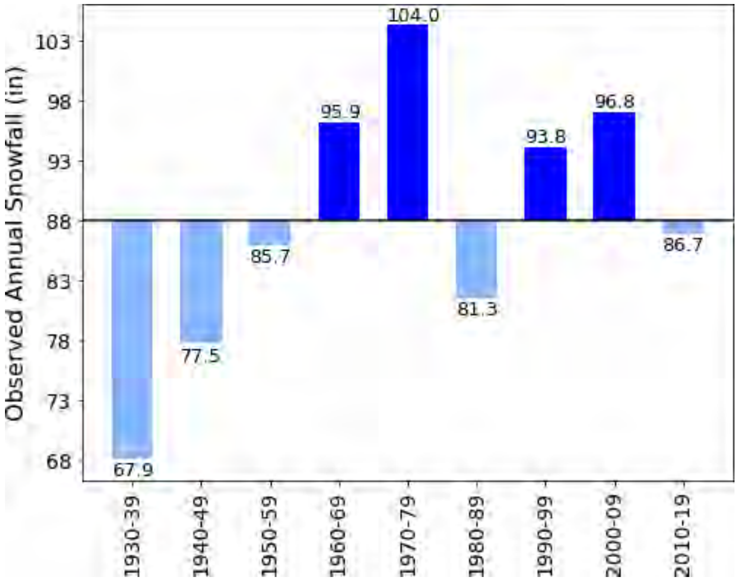

Figure 1-10: Decadal averages of observed annual snowfall in inches for the state of Vermont

Note: Decadal average values are plotted above and below the 1930–2020 mean value (solid black line). The table is computed based on available data for each decade, 1930–2020. Sufficient snowfall information for more than just the Northeast climate division starts in 1930.

Table 1-4: Trend and total change values in observed snowfall.

	Trend (inches per decade)			Total change (inches)		
	1930–2020	1960–2020	1991–2020	Since 1930	Since 1960	Since 1991
Snowfall (inches of snow)						
State of VT	**+2.1***	−1.8	−3.7	+18	−10	−11
Northeastern VT	**+3.3***	−1.0	−3.3	+24	−9	−10
Western VT	+2.1	−1.6	−5.5	+17	−12	−13
Southeastern VT	--	−3.5	−4.8	–	−17	−10
Winter precipitation (inches of liquid equivalent)						
State of VT	**+1.0***	**+0.3***	+0.3	+1.1	+1.8	−0.01
Northeastern VT	**+1.4***	+0.2	+0.01	+1.5	+1.8	−0.5
Western VT	**+0.7***	**+0.4***	**+0.7***	+1.1	+1.9	+0.6
Southeastern VT	+0.4	**+0.3***	+0.2	+0.6	+1.7	−0.3

Key (inches):

< -10	-10– -5	-5– -2	-2– -0.5	-0.5– 0	0–0.5	0.5–2	2–5	>5

Note: Trend values represent change per decade and those that are bolded and noted by an asterisk (*) are statistically significant to 95% confidence. Total change since 1930 is the difference between the 1930–1939 and 2011–2020 averages, total change since 1960 is the difference between the 1960–1969 and 2011–2020 averages, and total change since 1991 is the difference between the 1991–2000 and 2011–2020 averages. Total change values are not assessed for significance. Cells are color-coded based on their value using the key above. Computed on annual averages using available data for each year, starting in 1930 when there were consistent snowfall observations for northeastern and western climate divisions. Snowfall observations began in 1946 for southeastern Vermont, so the 1930s are omitted in that section.

1.6 CLIMATE INDICATORS

A series of climate indicators related to changes in precipitation and temperature trends are considered in this section. These climate indicators—including length of freeze-free period and the timing of the ice-out of lakes and ponds—affect how and when Vermonter's experience life, from planting of food crops to winter recreation.

1.6.1 Freeze-free Period

As temperatures in Vermont have warmed, the freeze-free period has lengthened. We define the freeze-free period as the number of consecutive days with a minimum temperature above 28ºF. This temperature threshold represents a hard freeze, an important factor for food production in Vermont (see Agriculture and Food Systems chapter). Since 1900, the length of the freeze-free period for the state of Vermont has increased at a rate of 1.7 days per decade, which accelerated to 4.4 days per decade since 1960 and and again to 9.0 days per decade since 1991 (Table 1-5; Figure 1-11). Southeastern Vermont has experienced the greatest change: from 136 freeze-free days in 1900 to 166 days in 2010s (Table 1A-5), with very rapid change since the early 1900s and early 1960s. Since 1991, northeastern Vermont has the most accelerated change in length of freeze-free period at 9.6 days/decade (Table 1.4).

Table 1-5: Trends and total change in the length of the freeze-free period

Freeze-free period	**Trend (days per decade)**			**Total change (days)**		
	1900–2020	**1960–2020**	**1991–2020**	**Since 1900**	**Since 1960**	**Since 1991**
State of VT	+1.7*	+4.4*	+9.0*	+21	+28	+16
Northeastern VT	+1.3*	+4.2*	+9.6*	+18	+28	+18
Western VT	+0.6	+2.4*	+5.5*	–2	+16	+10
Southeastern VT	+2.4*	+6.4*	+8.2*	+30	+37	+17

Key (days):

<0	0–5	5–15	15–25	>25

Note: Trend values that are noted by an asterisk (*) are statistically significant to 95% confidence. Total change since 1900 is the difference between the 1900–1909 and 2011–2020 averages, since 1960 is the difference between the 1960–1969 and 2011–2020 averages, and since 1991 is the difference between the 1991–2000 and 2011–2020 averages.

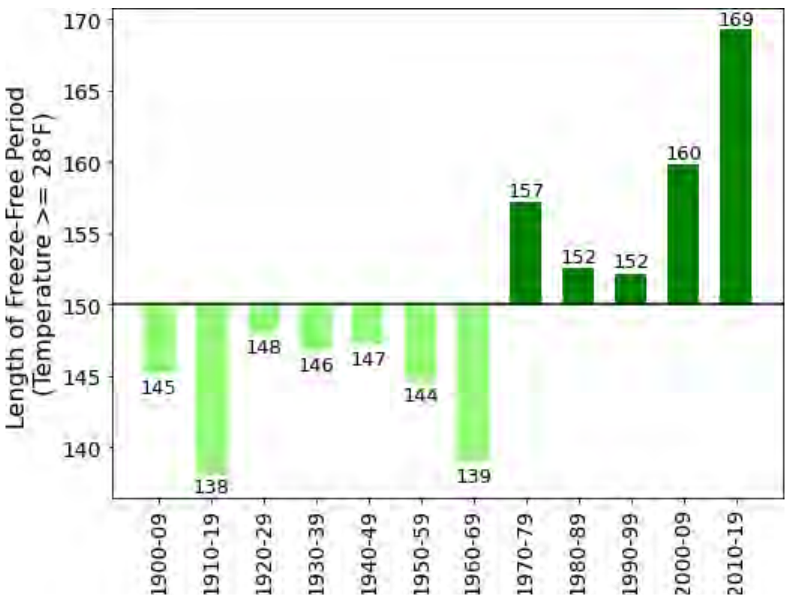

Figure 1-11: Decadal averages of the freeze-free period (consecutive days with minimum temperature above 28°F) for the state of Vermont plotted above or below the 1900–2019 mean (solid black line)

1.6.2 Ice-out on Vermont Lakes and Ponds

The day the ice melts off local ponds and lakes —the ice-out date—is noted by many Vermonters. Some take it as a sign of warmer days ahead, others mark it as the end of the ice recreation season, although ice is unstable long before it melts completely. While the definition of ice-out varies by water body, the ice-out date is generally when there is no longer full ice cover on a lake or pond. Ice-out dates have been used as a key climate change indicator. Ice-out dates reflect both the average winter and early spring temperatures as well as the timing and speed of the onset of spring. Earlier ice-out dates may reflect warmer average temperatures or an earlier, more rapid onset of spring, whereas later ice-out dates may reflect colder temperatures on average, or a later, more gradual onset of spring.

Many lakes and ponds in Vermont have ice-out records, usually through the efforts of citizen scientists. Some citizen groups use the ice-out date to run raffles: for example, the Joe's Pond Association sells tickets to guess the date and time, with the winner taking half the proceeds and the other half going to the annual 4th of July celebration. These citizen groups use simple and consistent methods that make for good long-term records of ice-out across Vermont.

In this research effort, six lakes and ponds across Vermont were assessed for ice-out trends using an ordinary least squares regression (Figure 1-12; Table 1-6): Lake Elmore (northeastern Vermont), Stiles Pond (northeastern Vermont), Lake Morey (northeastern Vermont), Joe's Pond (northeastern Vermont), Lake Iroquois (western Vermont), and Lake Rescue (southeastern Vermont). Five of the six lakes and ponds analyzed trend toward earlier ice-out dates, meaning that winter conditions that maintain ice-covered water bodies are likely being impacted by trends in winter temperatures (Figure 1-5; Table 1-2). For example, Joe's Pond in West Danbury, Vermont has seen ice out shift earlier at a rate of 3.4 days/decade since 1988 and Stiles Pond in Waterford, Vermont, has also seen earlier ice-out at a rate of 2.1 days/decade since 1971 (Table 1-6). Earlier ice-out dates not only impact winter recreation (i.e., ice sports; see Recreation and Tourism chapter) but also impact fish and wildlife (see Fisheries and Wildlife chapter) and the amount of discharge from rivers during the melt-season (see Water Resources chapter).

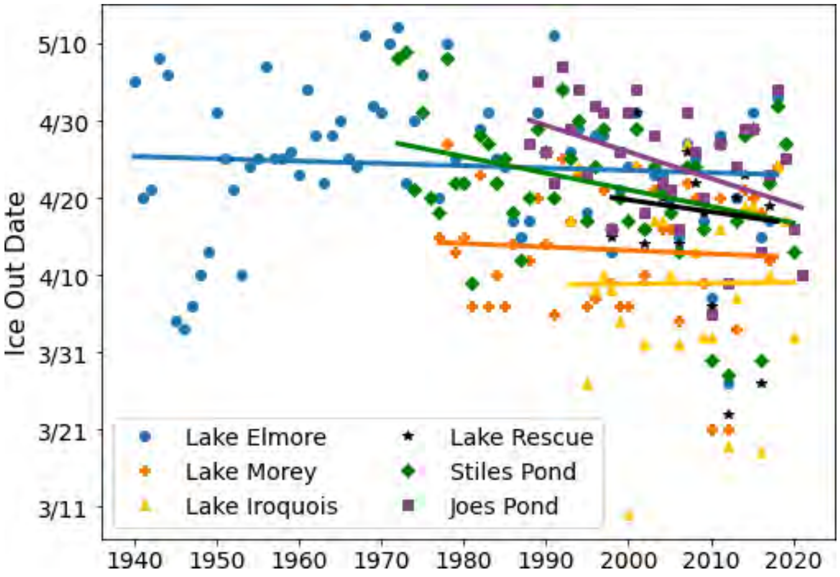

Figure 1-12: Annual ice-out dates for six lakes and ponds in Vermont with trend lines

Table 1-6: Trend in ice-out dates (days per decade)

	Lake Elmore[1] Elmore, VT	**Lake Morey[2] Fairlee, VT**	**Lake Iroquois[3] Chittenden County, VT**	**Lake Rescue[4] Ludlow, VT**	**Stiles Pond[5] Waterford, VT**	**Joe's Pond[6] West Danville, VT**
Period of record	1940–2018	1977–2018	1993–2020	1998–2018	1972–2020	1988–2021
Trend (days/decade)	−0.3	−0.4	+0.01	−0.2	−2.1*	−3.4*

Note: Values noted by an asterisk (*) are statistically significant to 95% confidence. Sources of data:
[1] Town of Elmore, 2021; [2] Town of Fairlee, 2021; [3] Lake Iroquois Association, 2021; [4] Lake Rescue Association, 2020;
[5] Data courtesy of Mark Breen, *Eye on the Sky*, Fairbanks Museum, St. Johnsbury, VT; [6] Joe's Pond Association, 2021.

Box 1.1: Vermont Winter Trends: Snow Cover, Ice-Out, and Winter Gardening

Contributor: Alan K. Betts, Atmospheric Research, Pittsford, Vermont

Amongst the climate changes apparent in Vermont, I find warming winters to be the most significant because winter temperatures are coupled to declining snow cover. Days without reflection of sunlight by snow are discontinuously warmer than days with snow (Betts and Desjardins, 2018).

Historically, most of Vermont was classified in climate zone 4, which corresponds to average winter minimum temperatures in the range -20°F (-29°C) to 30°F (-34°C). These minimums have risen at least 10°F in the past twenty years. This hastens ice out on lakes and ponds in spring and delays freeze-up in fall. This has been accurately monitored for Stiles Pond by the Fairbanks Museum for fifty years.

Figure 1.12 shows ice-out, freeze-up, and length of frozen period.

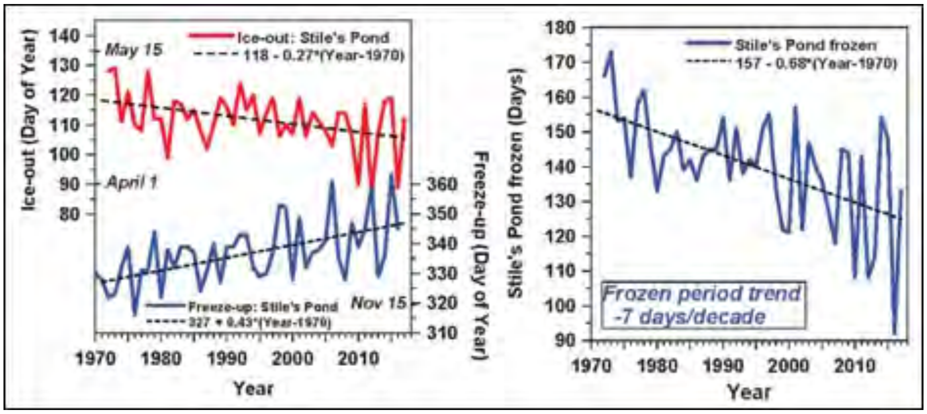

Figure 1-13: Ice-out, freeze-up and frozen period length for Sliles Pond, Vermont

The seven-day per decade trend towards a shorter frozen winter period is clear, but the interannual variability in the frozen period is now as large as the 46-year change in the trend line shown.

In Rutland County, I have planted a rye cover crop for 40 years. In the 1980s, the ground was solidly frozen all winter. By the early 2000s, the ground was often unfrozen into December. Figure 1-14 shows January 7, 2007 (left) the first January date that I was able to dig under my well-grown cover crop (left) after record temperatures in December; 2008 was similar. In 2012 the ground was frozen only 67 days (January 3 to March 10), and in 2013 the ground was unfrozen till mid-January. In the 2016 photo on the right of my granddaughter digging rye (Figure 1-14), a record was set because the ground was still unfrozen on February 5. There were unfrozen periods in January, February and March of 2017; 2018 was unfrozen into January, and 2020 was again unfrozen into February.

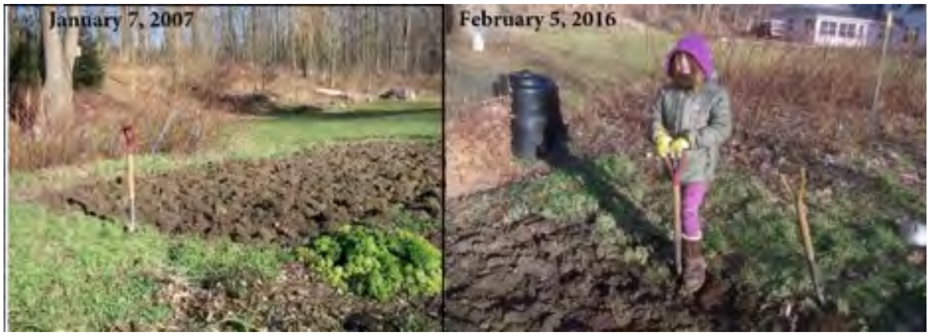

Figure 1-14: Digging rye cover crop on January 7, 2007 (left) and February 5, 2016 (right)

Winter gardening has transformed in a little over a decade, as soil temperatures have crossed the critical frozen-unfrozen threshold. Hardy crops like spinach and lettuce can be wintered over in glass-covered cold frames to give fresh vegetables in spring. Figure 1-15 shows these on April 20, 2021, with 8-in tall spinach (left) and buttercrunch lettuce heading up (right) together with smaller lettuce planted later in December.

Figure 1-15: April spinach (left) and lettuce (right) that have wintered in cold frames

1.7 EXTREME EVENTS

Climate change is expected to increase the variability in climate extremes. While some of the impacts of climate change on atmospheric, oceanic, and land-surface processes are known, the interactions of the changes across different spheres over time are less clear, since the climate will move in and out of historically rare climate states (Betts 2017). Extreme events can happen in Vermont in all seasons and include (but are not limited to): heavy precipitations (from tropical cyclones, severe thunderstorms) and variability in related events like flooding, heavy snowfall, ice storms, and drought.

1.7.1 Flooding

Flooding in Vermont can be caused by heavy precipitation (from tropical cyclones, winter storms, or severe thunderstorms) in all seasons or ice-jam flooding in the winter and spring. The most massive recent flooding event in Vermont was caused by Tropical Storm Irene on 28 August 2011; it resulted in an estimated $733 million dollars of damage and three fatalities (Runkle et al. 2017). In addition to the 4–8 inches of rain produced by Irene, existing high levels of soil moisture due to earlier heavy rain events in 2011 meant that much of Irene's record-breaking rainfall could not infiltrate into the soil and instead ran off the landscape directly into rivers. The heavy rains and large amount of runoff contributed to substantial flooding across the state, second only to the flooding caused by the Great Flood of 1927 (*Preliminary Hurricane/Tropical Storm Irene Weather Summary for the North Country* n.d.; *Top 5 Weather Events of 2011 across the North Country* n.d.). More recently, the Halloween storm of 2019 produced 3–5 inches of rain in a single day, broke multiple precipitation and temperature records, led to extensive flooding, and caused over $6 million dollars of damage to infrastructure across the state (Hastings and Taber 2019; *President Signs Disaster Declaration for Halloween Storm* 2020).

Ice-jams are a principal mechanism for winter flooding in Vermont. Ice-jams occur when warm temperatures, snowmelt, and rainfall cause ice in rivers to break up rapidly. This newly mobile ice accumulates and creates a dam, or ice-jam, causing water behind the ice-jam to rise, often topping riverbanks and filling floodplains. For example, from 12–14 January 2018, a combination of record warmth, record atmospheric moisture, a deep existing snowpack, and rains of 0.5– 2 inches led to ice-jams caused by rapid breaking up of river ice and resulted in flooding along the Missisquoi, Lamoille, and Winooski Rivers in Vermont (*The Widespread Ice Jam Flooding and Wintry Mixed Precipitation Event on January 12-13, 2018* n.d.).

1.7.2 Dry Spells and Droughts

Drought events in Vermont range from severe multi-year droughts that impact the entire state, to shorter lived, more frequent, localized events (Dupigny-Giroux 2001). The impacts of drought events can be far-reaching, affecting agriculture, water resources, forestry, and tourism in the state (Dupigny-Giroux 2001). Since the inception of the U.S. Drought Monitor (USDM) in 2000 (Svoboda et al. 2002), Vermont has experienced several significant droughts (Table 1-7). Vermont's longest drought since the start of this record lasted forty-five weeks (21 July 2016 to 25 April 2017), during which conditions ranged from moderately to exceptionally dry, or D1-D4 in the USDM drought classification (*Drought in Vermont from 2000-Present* n.d.).

More recently, Vermont experienced its most intense drought since the start of the USDM during the week of 29 September 2020, when severe drought conditions, D2 in the USDM classification, impacted 29.39% of the state. Extended periods with little-to-no precipitation and above-average summer temperatures (+6.2°F in Burlington, Vermont) resulted in the lowest seven-day average streamflow in September 2020 in 30 years for fourteen USGS streamflow gauges across New England (seven of which were in Vermont) (Figure 1-16; Lombard et al. 2021). Other notable droughts in the state occurred in 1930–1936, 1939–1943, 1960–1969, 1980–1981, 1988–1989, 1991, 1995, 1998, 2001-2002 (Dupigny-Giroux 2001, Table 1.6; Dupigny-Giroux 2002; Lombard et al. 2021).

Table 1-7: Droughts in New England. Table adapted from Table 1 in Lombard et al. (2021)

Year	**Months in which states were severely affected by drought,** defined as 30-year lows at more than 10 percent of sites
1991	June and July
1995	June to September
1998	May (Maine, New Hampshire, Vermont)
1999	June to August
2001	August to September
2002	August to September
2016	June to August
2020	June and September

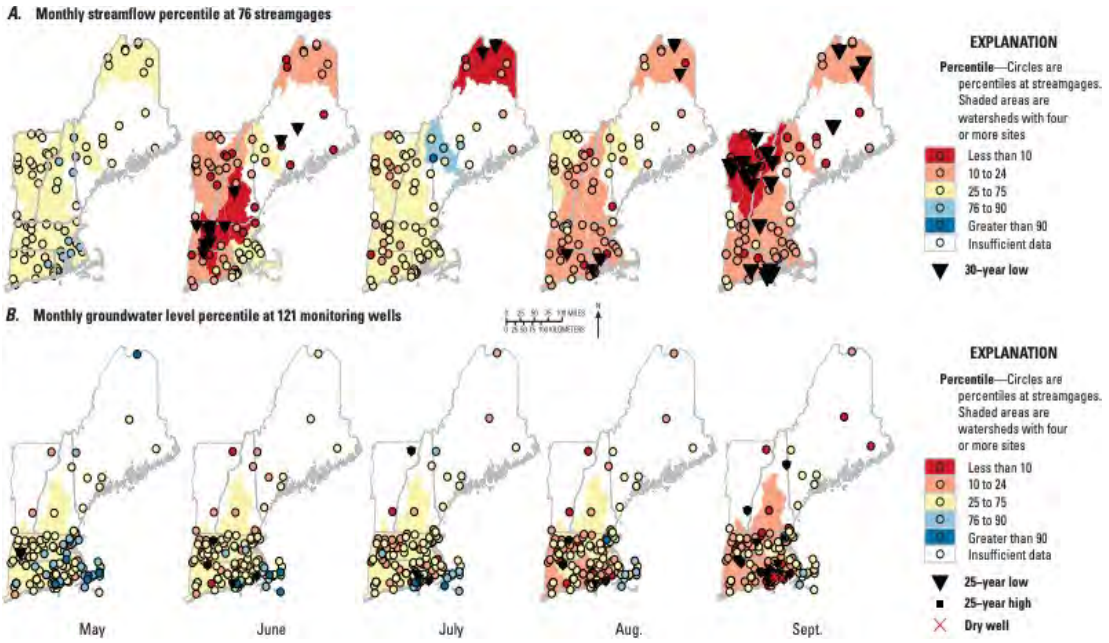

Figure 1-16: Maps showing (A) 30-year percentile for mean monthly streamflow at 76 stream gauges for streamflow conditions from May through September 2020 and (B) 25-year percentiles of monthly groundwater levels at 121 wells for groundwater conditions from May through September 2020

Note: Watersheds are based on the six-digit hydrologic unit code boundaries from U.S. Environmental Protection Agency and U.S. Geological Survey (2012). Watersheds with four or more sites are shaded according to the mean percentile across those sites. (Lombard et al., 2021; their Fig. 5)

1.8 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

Confidence level	**Very high**	**High**	**Medium**	**Low**
Description	Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus	Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message 1: **Vermont's annual average temperature has increased by almost 2°F (1.11°C) since 1900. Winter temperatures have increased 2.5 times faster than annual temperatures over the past sixty years, and the number of very cold nights has decreased by over seven days in the same time period.**	
Description of evidence base	Evidence for increasing long-term trends in temperature across Vermont were assessed using data from eighteen U.S. Cooperative Observer Network weather stations from 1888 to 2020.
Major uncertainties	Differences in the locations of stations (i.e., elevation, proximity to water body, land-use around station) mean that individual locations may be impacted by changes in temperature differently.
Description of confidence and likelihood	There is *very high* confidence that Vermont's temperatures have been and will continue to increase, especially in winter.

Key message 2: Average annual precipitation in Vermont has increased by 21% since 1900. Annual snowfall has been decreasing since a peak in the 1960s–70s, even as total winter precipitation has increased over the same time period, suggesting that more winter precipitation may be falling as rain.	
Description of evidence base	Evidence for increasing long-term trends in precipitation across Vermont were assessed using data from eighteen U.S. Cooperative Observer Network weather stations from 1888 to 2020.
Major uncertainties	While climate models for the Northeast United States project the greatest increases in winter and spring precipitation, historical records for Vermont show the fastest increase in summer precipitation. While annual snowfall for the last decade is still higher than in the earliest measurements, snowfall appears to have been declining since a peak in the 1960s-70s.
Description of confidence and likelihood	There is *very high* confidence that Vermont's precipitation has been and will continue to increase, and *high* confidence that more winter precipitation is falling as rain.

Key message 3: The length of the average freeze-free period is three-weeks longer now than the beginning of the twentieth century, and the rate of increase has accelerated in recent decades.	
Description of evidence base	Evidence for long-term trends in the length of the freeze-free period across Vermont were assessed using data from eighteen U.S. Cooperative Observer Network weather stations from 1888 to 2020.
Major uncertainties	Differences in the location of stations across the state (i.e., elevation, proximity to water body, land use around a station) may impact changes in the length of the freeze-free period differently.
Description of confidence and likelihood	There is *very high* confidence that the length of the freeze-free period has increased in Vermont and will continue to increase.

Key message 4: Lakes and ponds across Vermont are icing-out one-to-three days earlier per decade as compared to the 1970s and 1980s.	
Description of evidence base	Evidence for ice-out on lakes and ponds across Vermont comes from data produced by citizen science organizations.
Major uncertainties	Ice-out definitions differ slightly by location meaning that directly comparing trends from different lakes and ponds across Vermont is difficult.
Description of confidence and likelihood	There is very high confidence that ice-out on Vermont's lakes and ponds is occurring earlier.

<u>Key message 5:</u> Extreme weather events, such as droughts and floods, significantly impact Vermont. There are now 2.4 more days of heavy precipitation in the average year than in the 1960s. This increase has been happening about twice as fast in summer as in the other seasons.	
Description of evidence base	Evidence for the increase in heavy precipitation events in Vermont were assessed by using data from U.S. Cooperative Observer Network weather stations from 1888 to 2020
Major uncertainties	Much of the evidence for extreme events (i.e., droughts, tropical cyclones, floods) is anecdotal and localized, which makes trend analysis difficult. For example, systems that produce heavy precipitation events (greater than one inch) must pass directly over an observation site to be recorded.
Description of confidence and likelihood	There is *very high* confidence that heavy precipitation events are increasing in Vermont, due to the consistency of trends in these events across all observation sites. There is *high* confidence that extreme events will increase in Vermont.

1.9 APPENDIX TO CHAPTER 1

Table 1A-1: Station attributes for the stations used in this study

Station	Latitude	Longitude	Elevation (ft)	Climate division	Period of record
Barre Montpelier Knapp State Airport	44.2035	-72.5623	1125.98	Northeastern	1949–2020
Burlington International Airport	44.4683	-73.1499	330.05	Western	1941–2020
Cavendish	43.3847	-72.5988	842.00	Southeastern	1904–2012
Cornwall	43.9573	-73.2106	345.14	Western	1893–2020
Enosburg Falls*	44.9094	-72.8082	419.95	Northeastern	1892–2020
Gilman	44.4112	-71.7186	839.90	Northeastern	1931–2020
Island Pond	44.8128	-71.8902	1200.13	Northeastern	1991–2020
Mount Mansfield	44.5248	-72.8154	3950.13	Northeastern	1955–2020
Newport	44.949	-72.1912	790.03	Northeastern	1931–2020
Northfield	44.1647	-72.6567	669.95	Northeastern	1888–2017
Peru	43.26271	-72.90553	1700.13	Western	1941–2020
Rochester	43.8578	-72.8044	830.05	Northeastern	1929–2020
Rutland	43.6253	-72.9781	620.08	Western	1917–2020
Saint Johnsbury	44.42	-72.0194	700.13	Northeastern	1895–2020
South Hero	44.6264	-73.303	109.91	Western	1970–2019
South Lincoln	44.0725	-72.9736	1340.88	Western	1982–2020
Union Village Dam	43.7917	-72.2578	459.97	Southeastern	1951–2020
West Burke / Sutton*	44.6122	-72.0481	1500.00	Northeastern	1931–2020
Woodstock	43.6303	-72.5072	600.07	Southeastern	1893–2020

Note: Station names with an asterisk indicate stations that moved location at some point in their period of record. Current location is provided in the table.

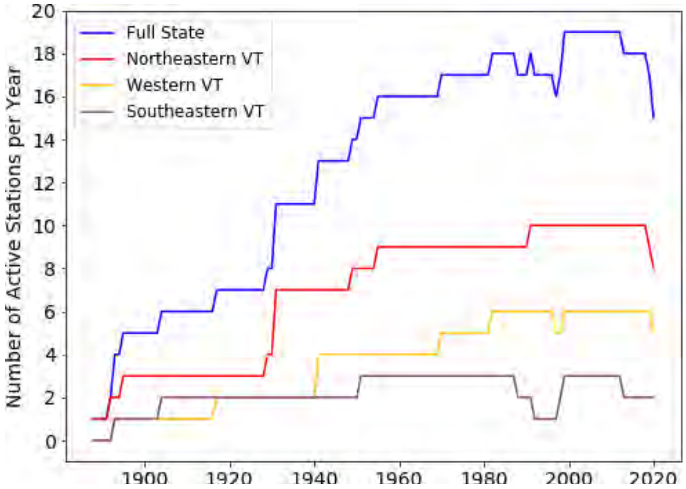

Figure 1A-1: Number of stations used for this analysis by year and location

Note: This number depends on the amount of data available each year as well as if a station was active or not (see Table A1 for each station's period of record).

Table 1A-2: Decadal mean values of temperature variables computed using annual averages with available data for each decade

Average temperature (°F)	Decadal mean value			
	1900–1909	1960–1969	1991–2000	2011–2020
Annual	42.1	42.6	43.0	44.1
Winter (DJF)	17.4	17.7	19.8	20.7
Spring (MAM)	41.3	40.5	41.1	41.4
Summer (JJA	64.7	64.3	65.2	66.2
Fall (SON)	46.0	46.6	45.8	47.6
Avg. Max. T. (°F)	53.4	53.4	53.6	54.5
Avg. Min. T. (°F)	30.9	31.1	32.4	33.7 ± 1.3
Days with Max. T. > 90°F (days)	3.4	3.8	3.6	4.9
Days with Min. T. > 70°F (days)	0.9	0.6	0.9	2.1
Days with Max. T. < 0°F (days)	35.8	35.0	29.0	25.0
Winter Days with Max. T. > 50°F (days)	2.0	2.02	4.0	3.8

Table 1A-3: Decadal mean values of precipitation variables computed using annual averages with available data for each decade

	Decadal mean value			
	1900–1909	**1960–1969**	**1991–2000**	**2011–2020**
Total precipitation (in)				
Annual	35.8	36.6	43.9	43.3
Winter (DJF)	7.3	7.0	8.8	8.8
Spring (MAM)	8.5	8.7	10.4	10.8
Summer (JJA)	11.1	11.0	12.8	13.6
Fall (SON)	8.4	9.6	11.6	10.9
Days with precipitation above 1 inch (days)				
Annual	6.2	5.8	8.0	8.2
Winter (DJF)	1.1	0.7	1.2	1.1
Spring (MAM)	1.2	1.0	1.7	1.8
Summer (JJA)	2.0	2.1	2.7	3.2
Fall (SON)	1.7	1.7	2.3	2.2

Table 1A-4: Decadal mean values of snowfall computed using annual averages with available data for each decade

Observed snowfall (inches of snow)	**Decadal mean value**			
	1930–1939	**1960–1969**	**1991–2000**	**2011–2020**
State of VT	68	96	96	86
Northeastern VT	73	105	106	97
Western VT	54	82	83	71
Southeastern VT	--	90	84	74

Table 1A-5: Decadal mean values of the length of the freeze-free period computed using annual averages with available data for each decade

Length of freeze-free period (days)	Decadal mean value			
	1900–1909	1960–1969	1991–2000	2011–2020
State of VT	145	139	150	166
Northeastern VT	143	132	142	160
Western VT	178	160	165	176
Southeastern VT	136	129	149	166

1.10 ACKNOWLEDGEMENTS

We acknowledge the helpful comments and suggestions on this work from Peter Banacos, Paul Sission, and Marlon Verasamy from the National Weather Service in Burlington, Vermont and from Alan Betts. We also acknowledge Mark Breen from the Fairbanks Museum in Saint Johnsbury for providing ice-out data for Stiles Pond.

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1.12 CLIMATE CHANGE IN FORESTS

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1.13 KEY MESSAGES

1. Climate change is beginning to shift growing conditions for forests in Vermont, with greater changes expected to come, becoming more favorable for southern-adapted tree species and less favorable for currently adapted tree species. Species that will benefit from this change include northern red oak, shagbark hickory, and black cherry, while species including sugar maple, balsam fir, yellow birch, and black ash will be negatively impacted. While growing conditions will be significantly different by 2100, actual change in forest makeup will follow a delay as older trees die and are replaced by young ones.
2. Forest productivity, an important indicator of forest health and carbon storage, is amplified by a longer growing season and greater atmospheric carbon dioxide (CO_2) and is expected to increase in Vermont in the next 50–100 years. However, productivity will be highly variable by species and will likely begin to decrease by the end of the century as high summer temperatures, drought, and soil nutrient loss outweigh benefits.
3. Climate change is expected to continue exacerbating the threats that invasive plants, insects, and diseases already pose to the health of Vermont's forests. These threats are compounded by other climate-related factors, such as worsening storms and increasingly irregular precipitation.
4. Warmer winters and wetter summers already limit active forest management by shortening the time frames that forest operations can take place. These negative climate impacts are projected to strengthen in the future, potentially leading to cascading negative effects on rural economies, forest product markets, and management for forest health and climate adaptation.
5. Land use change and parcelization, most commonly conversion of forests to residential or commercial use, is a persistent trend in Vermont, a major threat to forest health and productivity, and a contributor to climate change.
6. As climate change impacts forest ecosystem function, there is a need for management to increase forest adaptive capacity. Current methods to achieve increased adaptive

capacity at the ecosystem level (retaining ecosystem function despite threats to individual tree species or forest types) include increasing forest structural complexity and enhancing compositional and functional diversity and redundancy.

7. Climate change impacts will be more severe for urban trees because of the effects of the built environment on temperature and water cycling, as well as additional stressors associated with urbanized areas like soil compaction, soil fertility, and pollution.
8. Urban trees will be increasingly important to humans because of the services they provide. While urbanized areas in Vermont make up less than 2% of the state's land area, they are home to nearly 243,000 people, 39% of the Vermont population. Because of the high population density and lower tree cover in urbanized areas, per-tree ecosystem services can be higher than in a forest setting. In addition to critical climate and ecosystem benefits provided by trees everywhere, urban trees mitigate the urban heat island effect through cooling and shading and reduce stormwater runoff from extreme rainfall events.

1.14 FOREST STRUCTURE AND COMPOSITION

To understand the relationship of Vermont's forests to climate change, it is important to examine the current state of the forests' structure and composition. Forest structure can be broadly defined by elements such as trees and downed logs and the spatial arrangement of these elements (Franklin et al., 2002). Forest composition describes the number and distribution of species present in a forest. Both influence forest health, function, and resilience to climate change. Vermont's forest composition is projected to change as climate conditions shift, with warmer-adapted species expanding range across the region and colder-adapted species decreasing range to higher altitudes and latitudes (Iverson et al., 2019). Understanding how the existing forest will respond to climate change is essential to managing it and will impact objectives including conservation, recreation, and aesthetic benefits.

1.14.1 Historic and Current Forest Structure in Vermont

Vermont's forests have undergone several major shifts before developing into the largely northern hardwood-dominated forests found across much of the state today (Figure 2-1). The most recent drastic change was precipitated by European colonialism. Prior to European settlement, Vermont's forests were characterized by maple species and beech, with an increasing spruce-fir component further north (Cogbill et al., 2002). Although Indigenous communities utilized the forest, the dominant disturbances were small-scale weather events such as wind and ice storms (Seymour, 2005). For several centuries, land clearing for agriculture, building, and logging increased in Vermont until only 20% of the state remained forested in the late 1800s (Jeon et al., 2014).

During the 1900s, as agricultural production declined in Vermont in favor of more profitable lands elsewhere, forest cover reversed course and began increasing. This agricultural abandonment led to secondary forests (forests growing on previously cleared land) with an even-aged dominance of 80–100 years for most trees, minimal old growth, and some younger age classes arising (Figure 2-2). More recently, younger age classes face establishment challenges including deer browse and less-than-optimal regeneration conditions due to invasive species, as discussed in the Disturbance section.

Currently, forests cover 74% of Vermont, a slight decline from 78% near the turn of the twenty-first century. About 80% of Vermont's forests are owned by families and individual landowners; the remaining is mostly publicly owned, except for a small percentage under corporate ownership (USDA Forest Service, 2020). The most prevalent forest type in Vermont is northern hardwood, and the most prevalent overstory species is sugar maple (Acer saccharum). As climate change shifts many species' habitability ranges and intensifies disturbances, Vermont's forests may look as different 100 years from now as they did 100 years ago.

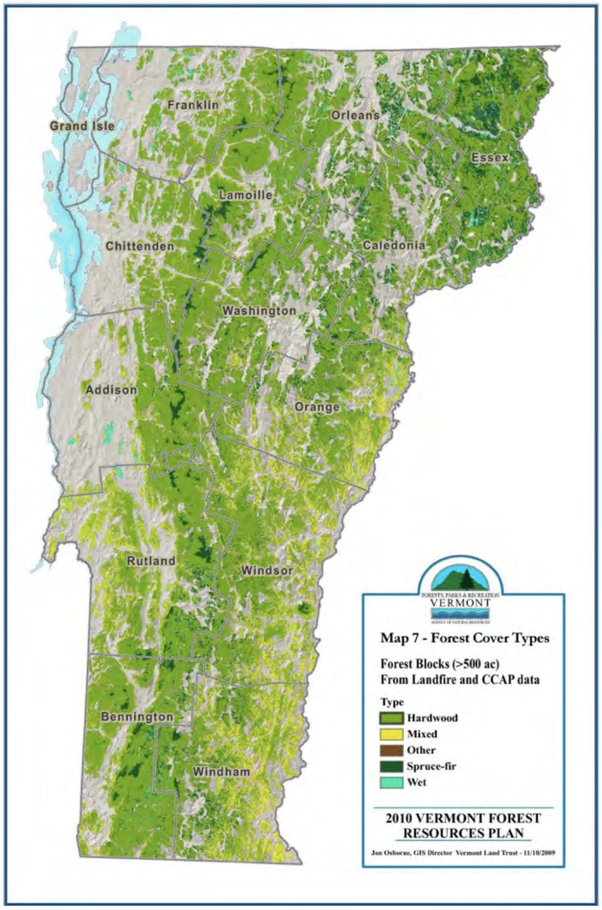


Figure 2-1: Forest types in Vermont circa 2010 (Vermont Forest Resources Plan, 2010)

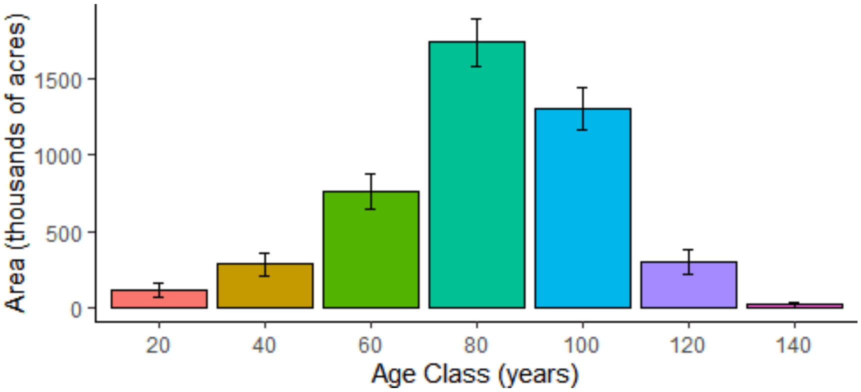


Figure 2-2: Vermont land area, in thousands of acres, covered by age class cohorts of forests based on Forest Inventory and Analysis sampling data

Note: Labels represent the upper limit of each age class; cohort ages are 1-20, 21-40, etc. Black bars represent sampling error at the 95% confidence interval (Morin, 2018, EVALIDator Version 1.8.0.01, 2021)

Forest resilience to climate change is tied to structural, compositional, and functional complexity at both the stand (local) and landscape scale. Within a forest stand, structural complexity relates to the arrangement of mixed elements, such as live and dead trees and downed logs; a structurally complex forest has a varied arrangement of these elements (Figure 2-3A). Landscape-scale structural heterogeneity (diversity of arrangement of structure types, including canopy gaps or groups of old trees) creates a variety of recovery pathways for forests and thus increases forests' ability to bounce back after a disturbance (Figure 2-3B). Compositional complexity and functional complexity are highly related. A compositionally complex forest has different species present in varying proportions. A functionally complex forest has trees that encompass a variety of functional traits as well as redundancy of these traits across the tree species present. Functional traits are related to plant colonization, survival, growth, and mortality, and they are strongly linked to ecological function (Violle et al., 2007). While species composition can provide information about diversity, it cannot provide specific information about biological function, ecological services, or occupation of ecological niches, all of which are valuable to understand ecosystem function (Messier et al., 2019). Diverse forests are resilient to a wider range of threats: for example, if a disease affects only a single tree species or a specific age class of trees, forests with greater variety in species or age classes will be less impacted by this disturbance than a simpler forest. Managing forests for structural, compositional, and functional complexity has multiple benefits, including enhanced habitat value, greater adaptive capacity, and carbon storage (D'Amato and Palik, 2020; Keeton, 2006). (See also Forest Adaptation section in this chapter.)

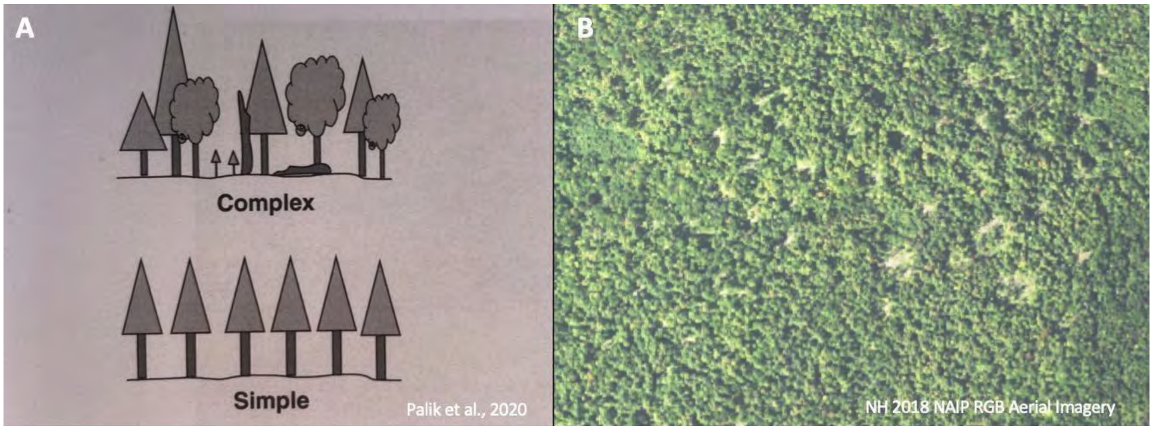


Figure 2-3: Structural complexity and heterogeneity at multiple scales in a forest

Note: A) A structurally complex vs. simple forest at the stand scale. The complex stand has species diversity, age class diversity, irregular arrangement of trees, and large downed woody material (Palik et al., 2020). B) At a landscape scale, this heterogenous forest contains canopy gaps of multiple sizes, uncut patches of forest in varying sizes, and thinned forest between these elements. Imagery from NH GRANIT (GranitView 2021)

1.14.2 Projected Changes to Forest Composition and Structure

As forest-type zones are predicted to shift northward, Vermont is predicted to become increasingly habitable for oak-hickory forests and less habitable for the northern hardwood and spruce-fir forests that currently dominate the landscape.

The USDA Climate Change Tree Atlas provides comprehensive data and current and projected future ranges for over 100 tree species. Future ranges are calculated using climate models. Each model considers a different set of variables and makes a different set of assumptions, so each model's predicted future conditions are slightly different. Figure 2-4 compares the current distribution of eastern United States forest types based on on-the-ground forest inventory data, to a potential 2100 distribution, calculated by averaging high-emissions scenarios for three models used to develop the General Circulation Model (Iverson et al., 2019; Peters et al., 2020). Figure 2-5 shows ecoregions in Vermont, and Table 2-1 breaks down the projected changes by tree species and ecoregion in the state.

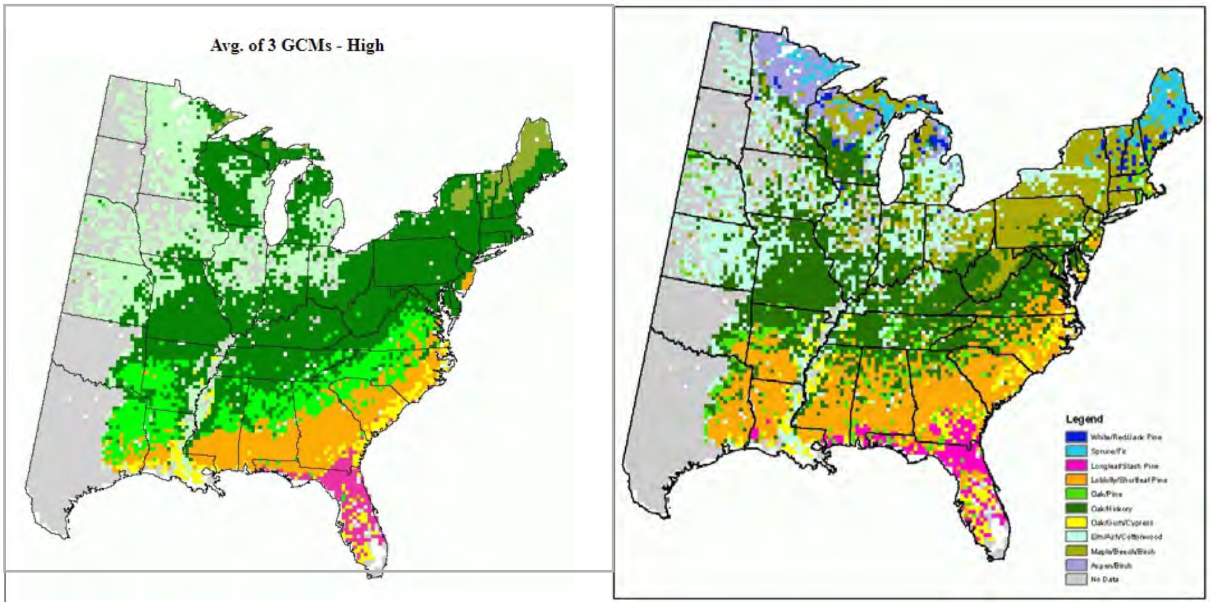


Figure 2-4

Note: The potential future distribution for the year 2100 is the result of averaging high-emissions scenarios of the three climate models making up the General Circulation Model (Peters et al., 2020).

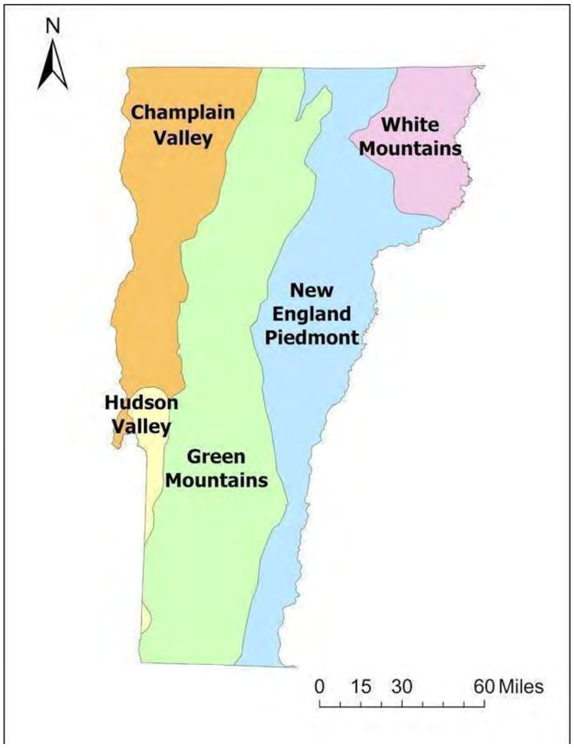
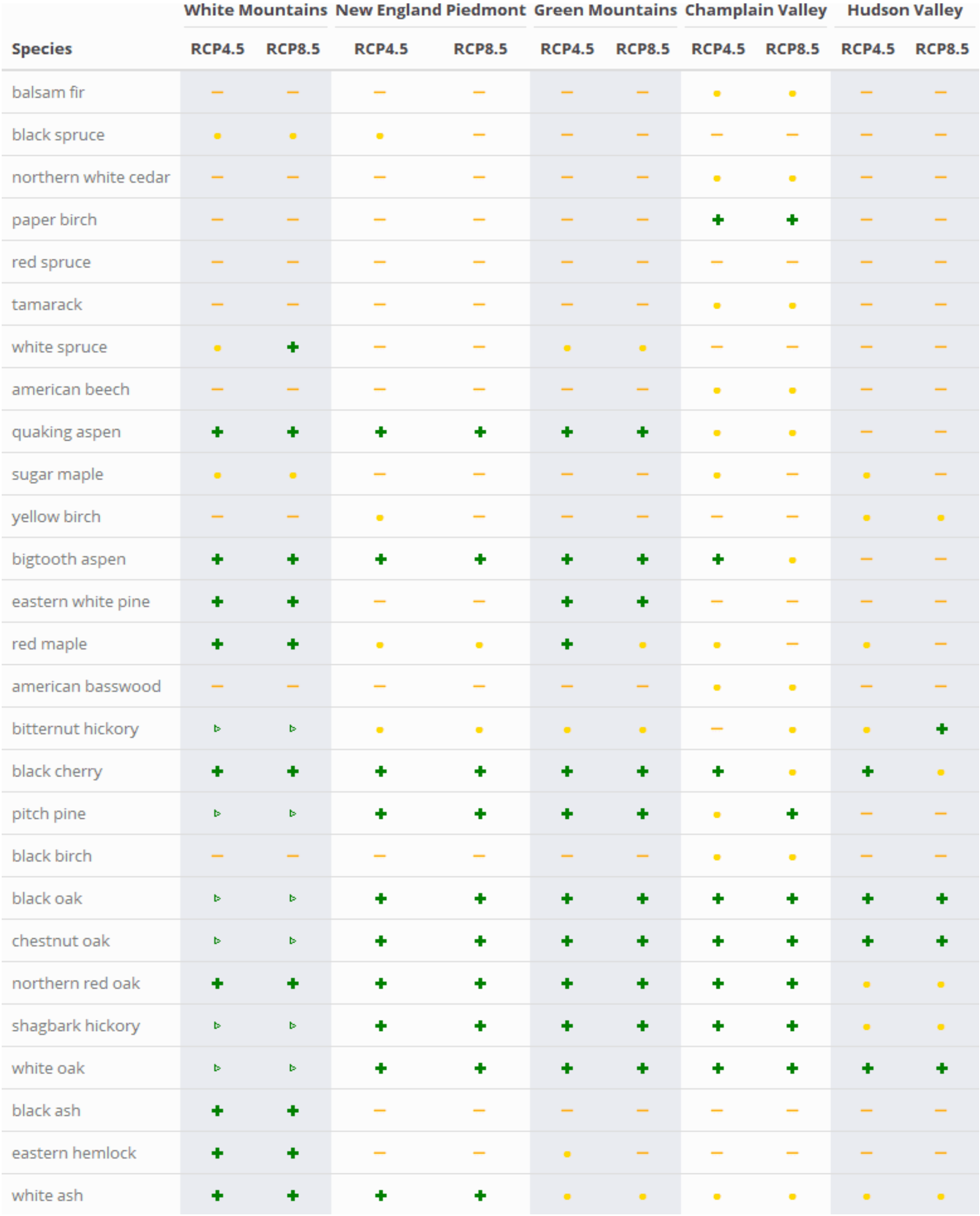


Figure 2-5: Vermont USDA EcoMap sections (U.S. Forest Service, 2017, Table 1)

Table 2-1: Projected species future range shifts in USDA EcoMap regions of Vermont



	White Mountains		New England Piedmont		Green Mountains		Champlain Valley		Hudson Valley	
Species	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
balsam fir	–	–	–	–	–	–	●	●	–	–
black spruce	●	●	●	–	–	–	–	–	–	–
northern white cedar	–	–	–	–	–	–	●	●	–	–
paper birch	–	–	–	–	–	–	+	+	–	–
red spruce	–	–	–	–	–	–	–	–	–	–
tamarack	–	–	–	–	–	–	●	●	–	–
white spruce	●	+	–	–	●	●	–	–	–	–
american beech	–	–	–	–	–	–	●	●	–	–
quaking aspen	+	+	+	+	+	+	●	●	–	–
sugar maple	●	●	–	–	–	–	●	–	●	–
yellow birch	–	–	●	–	–	–	–	–	●	●
bigtooth aspen	+	+	+	+	+	+	+	●	–	–
eastern white pine	+	+	–	–	+	+	–	–	–	–
red maple	+	+	●	●	+	●	●	–	●	–
american basswood	–	–	–	–	–	–	●	●	–	–
bitternut hickory	▷	▷	●	●	●	●	–	●	●	+
black cherry	+	+	+	+	+	+	+	●	+	●
pitch pine	▷	▷	+	+	+	+	●	+	–	–
black birch	–	–	–	–	–	–	●	●	–	–
black oak	▷	▷	+	+	+	+	+	+	+	+
chestnut oak	▷	▷	+	+	+	+	+	+	+	+
northern red oak	+	+	+	+	+	+	+	+	●	●
shagbark hickory	▷	▷	+	+	+	+	+	+	●	●
white oak	▷	▷	+	+	+	+	+	+	+	+
black ash	+	+	–	–	–	–	–	–	–	–
eastern hemlock	+	+	–	–	●	–	–	–	–	–
white ash	+	+	+	+	●	●	●	●	●	●

Note: Under medium-emissions (RCP4.5) or high-emissions (RCP8.5) scenarios, data from the Climate Change Tree Atlas predicts each species' suitable habitat range to increase (+), decrease (-), stay the same (●), or expand into the region (!). Modeled scenarios represent the future predicted conditions resulting from different concentrations of

greenhouse gas emissions (Iverson et al., 2019; Peters et al., 2020). Adapted from (Catanzaro et al., 2016).

Box 2.1: Vermont Sugar Maple

Sugar maple is Vermont's most common tree species. In addition to the usual tree benefits of shade and wood, its sweet sap plays a big role in the state. Maple syrup production is a major industry in Vermont, representing $54 million in revenue for sugar makers in 2019 (*Vermont Agency of Agriculture, Food & Markets 2019 Legislative Summary*, 2020). Because sap collection requires specific weather conditions of cold spring nights and above-freezing days, the changing climate may significantly impact maple syrup production in Vermont.

Future climate regime models predict that the habitable area for sugar maple will decrease overall, though some new habitat refuges for sugar maples will become available (Rapp et al., 2019). Climate change may also impact the forest tent caterpillar (FTC), a native insect that eats the leaves of sugar maple and other trees in Vermont. FTC outbreaks occur in periodic cycles, most recently in 2016-2018 (Vermont Department of Forests, Parks & Recreation, 2018). Shifting temperatures are likely to affect FTC survival and shift the synchrony between egg hatching and bud break, though it is not yet clear whether the net effect for sugar maples will be positive or negative (Uelmen et al., 2016). These hungry caterpillars can compound with climate change factors—such as earlier leaf-out dates, late spring frosts, and drought—to increase stress on sugar maples and make them less suitable for tapping (Oswald et al., 2018). In other words, trees already stressed by insect attacks are more vulnerable to the effects of unusual temperature and precipitation changes. Figure 2-6 shows the variance of average leaf-out dates of sugar maples over time; this is just one metric showing how unusual temperature and precipitation changes are influencing sugar maples.

The dates of highest sap flow are shrinking overall and shifting earlier in the season, requiring maple producers to change their schedules to keep up with current levels of production (Guilbert et al., 2014). In the future, even more limited dates of highest sap flow are projected, suggesting that a decrease in syrup production is likely unavoidable. Lower sugar content in sap is another change projected to intensify with the warming climate (Rapp et al., 2019). This means more sap will be required to produce each gallon of syrup, decreasing overall syrup yield for sugar makers.

In summary, direct climate impacts and increased stressors will likely negatively impact one of Vermont's leading industries. Surveys indicate that most maple producers already are aware of and adapting—or planning to adapt—to the effects of climate change, including by adopting new technologies and shifting where they obtain sap if current pathways become unreliable (Kuehn et al., 2017).

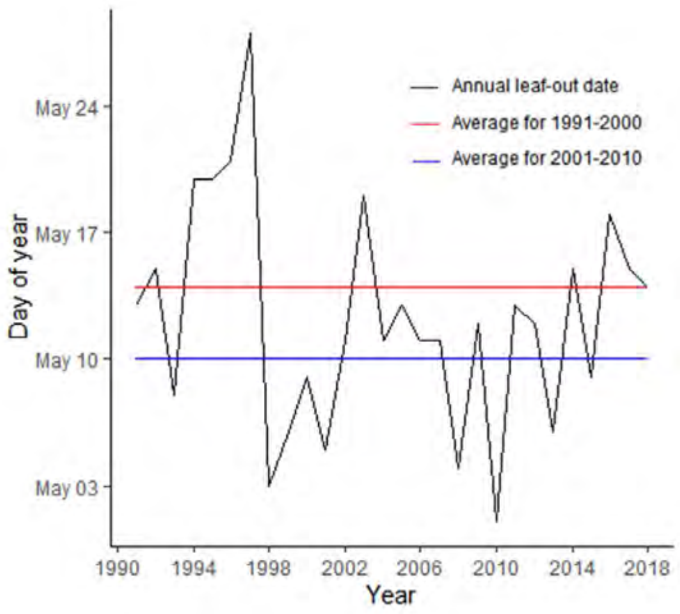


Figure 2-6: Average annual leaf-out date for sugar maples monitored in Underhill, VT (Halman and Wilmot, 2017)

1.15 FOREST PRODUCTIVITY

Forest productivity is a measure of how much and how quickly a forest grows over time. It is typically quantified as net primary productivity (NPP) in the unit of mass per unit area per unit time. “Net” represents the amount of productivity when taking into account losses, such as from respiration, and “primary” refers to photosynthetic producers in an ecosystem. Net ecosystem production is the physical biomass produced by plants in a forest through photosynthesis, which is mainly composed of carbon. A productive forest takes in carbon from the atmosphere and **sequesters** (captures from the atmosphere and stores) carbon in the molecules of leaves, branches, and roots. As such, productive forests can buffer the effects of climate change by sequestering more carbon from the atmosphere (IPCC, 2014). Much of this carbon is transferred to fungal partners associated with tree roots, making forest soils a major carbon sink and accounting for approximately 50% of Vermont’s forest carbon (Kosiba, 2021a; Steidinger et al., 2019). Productive forests also typically provide ecosystem services such as water filtration and storm protection, protect themselves against disturbances such as pest infestations and severe weather events, and more quickly recover from such disturbances.

There is moderate evidence suggesting that climate change will increase the carbon stored in Vermont’s forests in the next fifty years (Duveneck and Thompson, 2017; Janowiak et al., 2018) based on both computer modeling and empirical observations (Figure 2-7). On a finer scale, however, the effects of climate change on productivity are likely to vary both spatially and between species due to a combination of indirect climate effects (such as those that may alter soil microbial activity) and different trees’ levels of resilience and adaptability (to drought or extreme heat tolerance, for example). Table 2-2 describes confounding effects of changes caused by climate change.

The productivity of Vermont’s forests is influenced by management practices as well as climate change effects. While forests already store carbon, it may be possible to manage some forested areas for enhanced carbon storage, a desirable outcome considering emerging carbon markets. Carbon storage is just one of many desired management outcomes and must be balanced with needs relating to recreation, wildlife habitat, and economics, among others. (See also the forestry management section in this chapter).

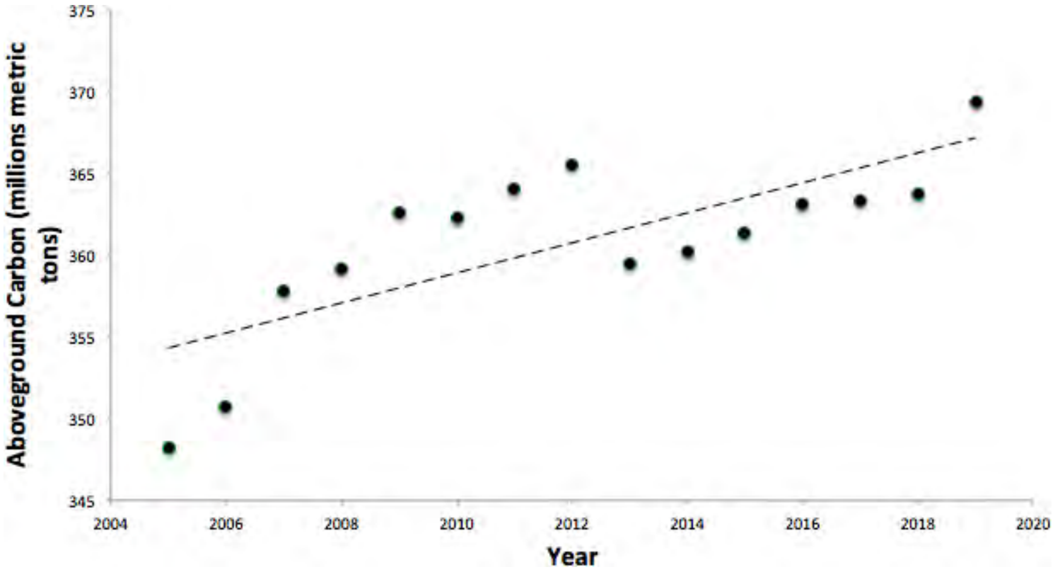


Figure 2-7: Carbon stored in Vermont's forests between 2005 and 2019 (FEMC, 2019)

1.15.1 Change in Length and Temperature of the Growing Season

Climate change, particularly warmer winter temperatures, is expected to increase the length of the growing season (Figure 2-8), which has already lengthened by three weeks since 1900 (see Climate Change in Vermont chapter). A longer growing season supports optimal conditions for photosynthesis for more days of the year. In one study of northeastern forests, a 1% increase in the growing season length resulted in a 1.6% increase in net ecosystem productivity (McMahon et al., 2010), with gains mainly in increased aboveground biomass. Interactions are likely to be more complex. Like animals, plants respire (breathe out), using carbohydrate sugars created through photosynthesis to produce energy. Respiration is positively correlated with temperature, so increased summer temperatures may cause increased respiration and may cause decreasing NPP in forests. However, gains in spring productivity are expected to exceed the increased summer respiration (Buermann et al., 2013; Duveneck et al., 2016;

Keenan et al., 2014). Respiration may exceed productivity in more extreme warming climate scenarios (e.g., RCP8.5) and/or for tree species that have low temperature optimums for photosynthesis (such as spruce) (Ollinger et al., 2008), although some young trees are able to adjust their physiology to photosynthesize more efficiently under warmer temperatures. In addition to respiration from plants, warmer temperatures have been shown to increase soil respiration from bacteria (Campbell et al., 2009), releasing some soil carbon and decreasing ecosystem productivity overall. By one estimate, temperate forest systems respire 10% of their total carbon, with that number increasing annually (Zhao et al., 2017). Another potentially damaging effect of extended growing seasons is warm spring temperatures that lead to earlier leaf-out may result in frost injury to trees, diminishing the benefit caused by the longer growing season (Hufkens et al., 2012).

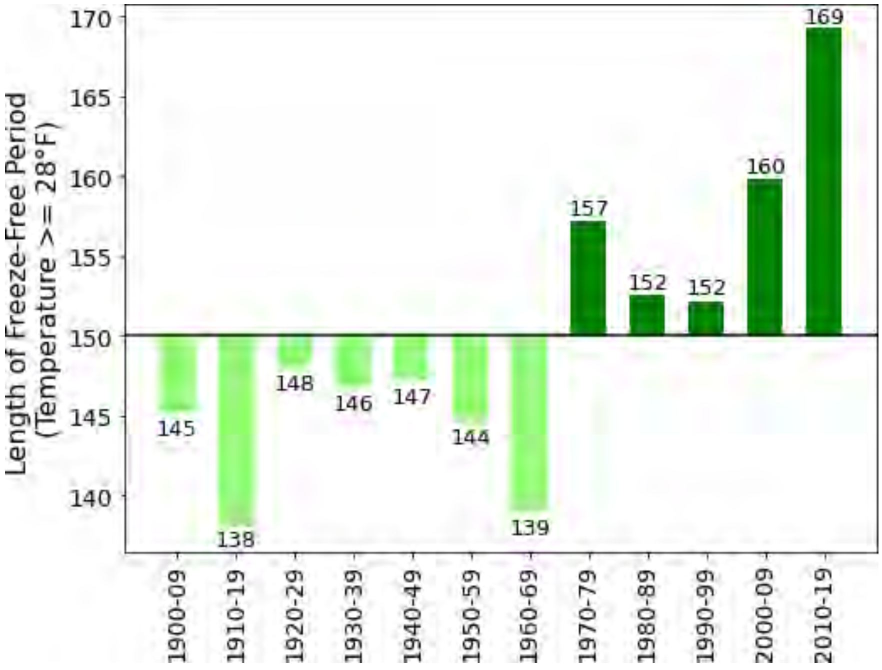


Figure 2-8: Length of Vermont's freeze-free period by decade (consecutive days with minimum temperature above 28°F) plotted above and below the 1900–2019 mean value (solid black line). (See Climate Change in Vermont chapter.)

1.15.2 CO_2 Fertilization Effect

"CO_2 fertilization" is a phenomenon in which increased levels of atmospheric CO_2 enhance photosynthesis rates, thereby increasing tree and plant NPP. Globally, there is potential for forests to sequester more CO_2 and effectively lower atmospheric CO_2 concentrations (Figure 2-9). Studies have found that elevated atmospheric CO_2 concentrations can increase the optimum temperature for photosynthesis in some species and increase plants' water use efficiency, promising signs that forests may become even more productive and efficient in water use, at least through the next fifty years (Ollinger et al., 2008; Rayback et al., 2020; Sperlich et al., 2020).

While climate change may increase productivity via CO_2 fertilization, these benefits may be offset by warming-induced water and nutrient stress (Norby et al., 2010). Additionally, disturbances that interact with climate change—such as fire, insect infestations and increased herbivore populations—will decrease productivity (Couture et al., 2015). The net effect depends on the interactions among atmospheric CO_2 concentrations, the sensitivity of tree species to heat, drought and nutrient stress, and external disturbances. For example, the extent to which CO_2 fertilization enhances the productivity of spruce forests is limited by their sensitivity to temperature increases. To an extent, the higher NPP and water use efficiency resulting from increased CO_2 may allow trees to be nominally more resilient to disturbances brought on by climate change, although more research is needed to determine this.

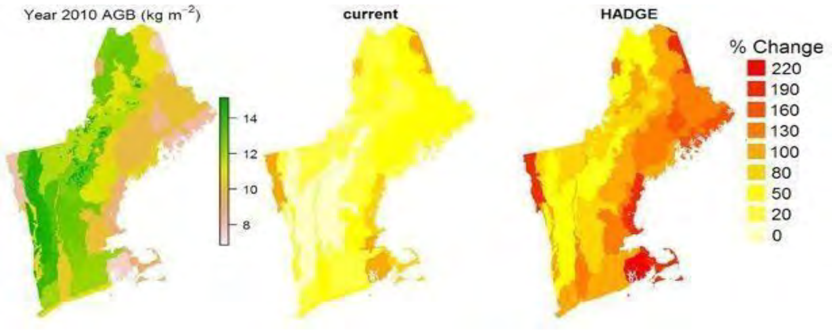


Figure 2-9: Average simulated aboveground biomass (AGB) in kg/m2 in 2010 and percent change in AGB from 2010 to 2110 under the HADGE-modeled climate change scenario, based on current conditions and absent major disturbance

Note: HADGE = Hadley global environmental model v2 - earth system (modified from Duveneck et al., 2016)

1.15.3 Impacts to Nutrient Cycling

To carry out their metabolic processes and produce biomass, trees and other plants rely on nutrients and water from soils. Two of the most important nutrients are phosphorus and nitrogen. Phosphorus is deposited in soils through the weathering of rocks. Nitrogen is abundant in the atmosphere, but most plants can use it only if it is converted to a compound called nitrate (NO_3) by nitrogen-fixing bacteria that live in soils and the roots of some leguminous plants. Nitrogen is generally a growth-limiting nutrient in temperate forest ecosystems because nitrate occurs in low concentrations (Campbell et al., 2009).

Warming spring temperatures cause snowpack to disappear earlier in Vermont, impacting nutrient cycling in different ways. Snowmelt may leach nutrients from the soil when it occurs before photosynthesis has resumed and plants can retain nutrients (Contosta et al., 2017; Groffman et al., 2012). Earlier peak snowmelt may limit water availability during the height of the growing season (Wilson et al., 2020), depending on spring and summer rainfall. A combination of earlier snowmelt and decreased snowpack depth (see Climate Change in Vermont chapter) exposes soils to colder temperatures since snowpack tends to insulate soils. Soil-freezing events damage plants' root tissues so they take up less nitrogen, leading to leaching of nitrogen from the soil over time (Campbell et al., 2014). Under a changing climate, temperature, precipitation, and biogeochemical cycles will interact in new ways that is highly likely to cause a net decrease in key nutrients in Vermont's soils, limiting the growth of forests and forest productivity.

1.15.4 Impact to Beneficial Plant-Fungus Relationships

Soil microbes and fungi play a large role in the productivity of forest ecosystems. Ectomycorrhizal (which surround plant roots) and arbuscular mycorrhizal (which penetrate plant roots) are two of the most abundant root-colonizing fungi that provide trees with critical nutrients and, in exchange, receive carbon from tree roots. These fungi are crucial to carbon sequestration and storage in forest ecosystems.

Certain types of fungal symbiotic partners, in particular ectomycorrhizal fungi, dominate in forests where seasonally cold and sometimes dry conditions inhibit decomposition and where nitrogen is a limiting nutrient—as in Vermont. These fungi have evolved symbiotic relationships with 60% of all tree species, mainly in higher latitudes and altitudes (Steidinger et al., 2019). However, as environmental conditions become more like lower latitudes and altitudes (e.g., warmer, wetter), these fungi are threatened. Declines in such fungi could cause declines in the trees adapted to them, including beech (*Fagus grandifolia*), white pine (*Pinus strobus*), oaks (*Fagus spp.*), and many other northern hardwood species. However, when combined with other climate adaptability indicators of tree species, different patterns emerge. For example, the range of oak species may expand (Figure 2-4, Table 2-1). Change in fungal composition in Vermont's soils along with increasing temperature and precipitation will facilitate changes in the composition of forests (Classen et al., 2015). Changing temperature and precipitation regimes are also compromising the functionality of the fungi and microbes, which trees depend on to assimilate nutrients from the soil, causing negative impacts on productivity that may not be mitigated by longer growing season length and CO_2 fertilization.

1.15.5 Atmospheric Deposition

Humans release many compounds that can affect forest productivity to the atmosphere. For example, volatile sulfur and nitrogen compounds originating from industrial activities are deposited from the atmosphere by rain and snowfall in relatively high concentrations in the northeastern United States ("atmospheric deposition") (Pardo et al., 2011), though the production of these compounds is expected to decrease because of measures to reduce greenhouse gas emissions. Atmospheric deposition of nitrogen and sulfur to soils can alter the biogeochemistry of forest ecosystems. Nitrogen saturation has been shown to decrease the allocation of carbon to mycorrhizal fungi, weakening the essential relationship between trees and fungi (Frey et al., 2014). Nitrogen and sulfur deposition has been shown to make trees more vulnerable to drought and insect infestations, weakening resilience to climate change (McNulty and Boggs, 2010; Pardo et al., 2011), and acid deposition can leach nutrients from foliage and forest soils, leading to nutrient depletion (DeHayes et al., 1999). While atmospheric deposition is not a direct effect of climate change, it comes from the same root cause (e.g., human combustion of fossil fuels). The use of products containing nitrogen and sulfur increased for many decades before regulations began limiting production. There are indications of ecosystem recovery from some of these pollutants (Kosiba et al., 2018) but stress brought on by climate change could exacerbate the negative effects of nitrogen and sulfur deposition.

Ground-level ozone is an atmospheric pollutant that affects stomatal control, decreases water use efficiency, and damages plant tissues, thus causing water stress and decreased biomass and productivity. Plants with increased ozone exposure have declines that offset gains in productivity from CO_2 fertilization (Mohan et al., 2009; Rustad et al., 2012) Ozone levels are closely linked to the presence of nitrogen oxides (products of fossil fuel combustion) in the atmosphere, so decreased ozone emissions could have positive effects for forest productivity barring negative interactions with other climate change stressors.

Table 2-2: Factors interacting with climate change and affecting productivity for forest ecosystems in the Northeast

Confounding factor	Effect
Nutrient availability	Less fertile soils, characterized by declines in essential nutrients such as nitrogen and phosphorus, are expected due to a combination of increased 1) decomposition rates, 2) leaching of soil nutrients due to earlier snowmelt and increased precipitation events, and 3) uptake rates by plants with enhanced metabolisms due to CO_2 fertilization.
Water availability	While Vermont has experienced increased annual precipitation, there are two factors that could lead to water limitation: 1) Earlier onset of snowmelt, if not mitigated through rainfall, will lead to lower water table levels. 2) Warmer temperatures will increase rates of evapotranspiration from plants and lead to a decrease in water use efficiency.
Heat stress	Tree species that are intolerant to intense heat, such as spruce, may experience declines in productivity in the summer.
Biotic stressors	Climate change is expected to increase the prevalence of pests and pathogens (see the disturbance section in this chapter), invasive species, and herbivores (such as white-tailed deer) due mainly to milder winters. The range and fecundity of these species will expand and become more established in Vermont. Most tree types will experience direct decreases in biomass and productivity due to biotic stressors.
Arrested succession	Both native and invasive plant species can form dense, monodominant understories. Such understories can form quickly after disturbances, particularly where excessive deer grazing favors the proliferation of less-desired browse species. Dense understories can limit forest regeneration, outcompeting slower growing trees for physical space, nutrients, and sunlight, and thus arresting forest succession.
Atmospheric deposition and acid rain	Acid deposition in the Northeast originates from industrial activities producing nitric or sulfuric oxide emissions that combine with atmospheric water vapor to form acid rain. Acid deposition could increase with increased precipitation events, though high levels of water vapor may also dilute effects, or emissions may be reduced through emissions reductions. The impacts of atmospheric deposition and acid rain on nutrient availability will especially affect high-elevation spruce/fir forests, which are already suffering from heat stress.

1.16 DISTURBANCE

Ecological disturbance (e.g., high winds, fire) plays a major role in forest structure and function. Climate change may compound the effects of biotic disturbances such as invasive forest pests, plants, and pathogens. Simultaneously, climate change is projected to increase the frequency and severity of abiotic stressors, such as extreme weather events (Reidmiller et al., 2018). Forests are constantly responding to minor disturbances, but the expanding frequency and intensity of these stressors is unprecedented in recent times. In addition, disturbances may interact; for example, more frequent stand-replacing weather events may provide better habitat for shade-intolerant invasive plants that can aggressively displace native species (Dukes et al., 2009).

1.16.1 Biotic Disturbances

Forest pests and pathogens, herbivores, and invasive plants are all agents of disturbance in Vermont's forests, and they intersect with climate change to varying degrees. Of the many exotic species brought to the United States intentionally or unintentionally each year, a fraction are considered invasive due to their abilities to aggressively spread, kill, or displace native species. Non-native insects and diseases may functionally eliminate a tree species or group of species, such as ashes or hemlocks, significantly altering the forests in their invasive range (Lovett et al., 2016). Others, such as a group of fungal pathogens known as anthracnose disease, inflict low-level stress on a variety of species, contributing in conjunction with other factors such as drought or changing climate suitability to overall forest decline. Although effects vary among species, in many cases warming trends enable invasive species to spread faster by decreasing winter mortality and increasing reproduction rates (Seidl et al., 2014). Table 2-3 summarizes the impacts and climate interactions of several non-native pests and pathogens of concern in Vermont, including some that are already established in the state and others that may arrive soon.

Invasive plant species represent a different threat to Vermont's forests. Instead of directly killing trees, they out-compete native plants, including many understory species, and take up sunlight and other resources. Although invasive plants are found in different habitats and conditions, they are often shade-intolerant and spread or reproduce prolifically. Increasing forest fragmentation and human-caused disturbances, along with native species that are more vulnerable due to climate change, lead to increased dominance by invasive plants. Invasive plants displacing native plants have ripple effects through the ecosystem: they remove food sources for wildlife and alter soil chemistry, nutrient cycling, and water cycling (Fisichelli et al., 2014).

Repeated disturbances often lead to reduced diversity and proliferation of dense understories that prevent or delay the natural succession of forests; these dense, monodominant patches are called recalcitrant understories. Recalcitrant understories are usually composed of fast-growing and browse-tolerant species that increase light percolating to the forest floor. They are caused by excessive deer grazing in tandem with outbreaks of diseases or pests, such as the LDD moth (*Lymantria dispar)* (Royo and Carson, 2006). Fundamentally, canopy disturbance and ground level manipulation are likely to significantly alter the successional trajectory of forests. Causes—including deer browse and disease outbreaks—are expected to increase in frequency and severity in Vermont because of climate change (see Fish and Wildlife in Vermont chapter). Further, pressure from deer browsing may limit the ability of forest ecosystems to respond to climate change (Fisichelli et al., 2012). The outcome for many of the hardwood species valued in Vermont is less vigorous regeneration. Deer browsing combined with other climate stressors could contribute to the decline of forest types in Vermont.

Table 2-3: Invasive pests and pathogens of current or future concern in Vermont forests

Pest or pathogen	**Description**	**Species impacted**	**Geography**	**Climate interactions**	**References**
Balsam woolly adelgid (Adelges piceae)	Small, aphid-like insect that feeds on trees' internal tissues, particularly older trees	Balsam fir (Abies balsamea)	Statewide in VT	Populations are limited by temperature extremes, expanded by milder seasons in comparable forests in other regions	Hrinkevich et al., 2016; Quiring et al., 2008
Beech bark disease (*Nectria* fungi) and beech scale insect (*Cryptococcus fagisuga* insect)	Combination of at least two fungal infections and sap-feeding scale insects that weaken trees, affecting their ecological values	American beech (*Fagus grandifolia)*	Statewide in VT	Increasing periods of drought make beech more vulnerable to factors like beech bark disease, as beech is less climate resilient than many other hardwoods. Milder winters favor beech scale insect	Stephanson and Coe, 2017

Earthworms	Variety of worm species originating in Europe accelerate litter decomposition, altering forest floor structure	Many overstory and understory species	Statewide in VT	Overstory and understory species are impacted by the changes worms make on the soil profile, which affects regeneration of species and moisture retention in the soil. It is likely to amplify other climate effects like changing precipitation regimes and soil communities	Dobson and Blossey, 2015
LDD moth (Lymantria dispar dispar)	Moth whose caterpillar feeds on leaves of many trees, with rapid population growth occurring in irregular outbreaks; consecutive years of defoliation can kill trees	Oaks (Quercus spp.), apples (Malus spp.), maples (Acer spp.), birches (Betula spp.), and many other species	Statewide in VT	Drought leads to LDD moth outbreaks because it limits the growth of a fungus that kills and weakens LDD. Climate change is likely to increase the variability and extremity of weather patterns, including extended periods of drought that could lead to more frequent LDD outbreaks & more severe impacts in the future	Davidson et al.., 1999
Anthracnose disease	Various species of fungus causing leaf damage that weakens and rarely kills trees	Maples (Acer spp.), ashes (Fraxinus spp.), oaks (Quercus spp.), sycamores (Platanus spp.), dogwoods (Cornus spp.), and others	Several locations across VT	Thrives in moist conditions, so changing precipitation regimes may affect its spread, frequency, and severity; susceptible tree species may increase or decrease range in Vermont due to climate change	Holzmueller et al., 2010; Vermont Forest Health, 2011

Elongate hemlock scale (Fiorinia externa)	Scale insect that feeds on needles, stressing trees in combination with hemlock woolly adelgid	Eastern hemlock (Tsuga canadensis)	Several locations across VT	Demonstrated ability to adapt locally to different temperatures may enable its continued spread throughout hemlock's range	Preisser et al., 2008
Emerald ash borer (EAB) (Agrilus planipennis)	Green beetle feeding on inner bark and sapwood in its larval stage, weakening and usually killing trees	Ashes (Fraxinus spp.)	Several locations across VT	Ash and EAB ranges are predicted to shift under climate change; phenological mismatch between EAB and biocontrol agents may occur	Jones et al., 2020; Liang and Fei, 2014
Hemlock woolly adelgid (Adelges tsugae)	Small, aphid-like insect that feeds on trees' stored starches	Eastern hemlock (Tsuga canadensis)	Windham, Bennington, and Windsor counties as of 2019	Currently restricted to southern VT due to cold winter temperatures, but warming winters may expand range northward	McAvoy et al., 2017
Sirex woodwasp (Sirex noctilio)	Large, wood-boring insect often transported through wood packaging and firewood	Pines (Pinus spp.)	Present in VT (detected in Lamoille County as of 2008)	Trees stressed by changing climate factors (e.g., increased drought) are more vulnerable to infestation by this pest	Slippers et al., 2011
Asian longhorned beetle (Anoplophora glabripennis)	Large black and white-spotted beetle that feeds on wood in its larval stage, weakening host trees	Hardwood species including maples (Acer spp.), ashes (Fraxinus spp.), birches (Betula spp.), poplars (Populus spp.), and more	Not detected in VT; present in MA and NY	High temperatures and precipitation limit Asian longhorned beetle dispersal, but effects are not consistent across its range	Huang et al., 2020

Spotted lanternfly (Lycorma delicatula)	Leafhopper insect feeds on sap, stressing and sometimes killing trees	Maples (Acer spp.), birches (Betula spp.), grapevines (Vitis spp.), and many other species	Not detected in VT; present in NY, CT, PA, and NJ	Often co-occurs with tree-of-heaven, its preferred host species, and an aggressive invasive plant	Urban, 2020
Winter moth (Operophtera brumata)	Caterpillar that feeds on buds and new leaves in spring	Oaks (Quercus spp.), maples (Acer spp.), birches (Betula spp.), apples (Malus spp.), blueberries (Vaccinium spp.), and others	Not detected in VT; present in MA, RI, NH, ME, CT, and NY	Warmer winters may allow it to expand its range into Vermont; changing weather disrupts winter moth's synchrony with host tree bud break, some shift to other species	Elkinton et al., 2015

Box 2.2: Emerald Ash Borer and Climate Impacts in Vermont

Emerald ash borer (EAB; Figure 2-10) is one of the most destructive invasive forest pests in the United States. This shiny green beetle, native to Asia, feeds on ash tree sapwood and inner bark in its larval life stage, weakening and eventually killing trees. Its spread has caused economic, ecological, and cultural losses as it has killed millions of ash trees in cities and forests (McCullough, 2020).

Figure 2-10: An adult emerald ash borer. Photo: USDA-APHIS, 2012

EAB’s rapid expansion in North America is largely attributed to unintentional human movement through infested firewood. Quarantine regulations helped keep EAB out of Vermont for many years, but it was first detected in Vermont in 2018 (Figure 2-11) and has since spread to several locations (“Emerald Ash Borer (EAB) Infested Area in Vermont,” 2021). Avoiding movement of firewood is still encouraged to slow its spread, but at this point EAB is likely to continue to expand its range throughout Vermont’s forests.

Climate change may alter the dynamics between EAB and ash trees in North America, though these effects are likely to take place on a longer time scale than the current speed of EAB-induced mortality. One study suggests that climate change will exacerbate EAB's impacts in the northern part of its invasive range, including Vermont, because the future climate will be more favorable to EAB (Liang and Fei, 2014).

While there is no silver bullet that can prevent EAB, there are several options to manage EAB and forests containing ash. They include:

Chemical control: The pesticide emamectin benzoate is highly effective at protecting individual ash trees from EAB, but its expense and impermanence limits its widespread use. It can be combined with girdling "trap" trees to attract and then kill EAB.

Biological control: Several EAB parasitoids from its native range have been released in the United States in efforts to reduce pest populations. Though they are not available for individual use, growing populations may contribute to landscape-level EAB control, most often used in conjunction with other methods.

Genetic resistance: A small proportion of North American ash trees display natural resistance to EAB, and research efforts are underway to identify these individuals, understand their mechanisms of defense, and breed them to create more resistant ash stock.

Silvicultural strategies: When managing forests with ash for EAB, it is important to keep in mind that diverse forests are resilient forests. Retaining some mature ash in the face of EAB allows resistant individuals to persist and reproduce. The habitable range for white ash in Vermont is predicted to increase, and if it can be preserved to some extent through the immediate threat of EAB, ash may continue to be an ecologically significant component of Vermont's future forests (D'Amato et al., 2020).

Figure 2-11: A forest harvested partly in response to emerald ash borer invasion. Photo: Hanusia Higgins

Box 2.3: LDD Moth (*Lymantria dispar dispar*) Outbreak of 2021

In 2021, Vermont and other parts of New England saw the largest outbreak of the *Lymantria dispar* (LDD) moth (Figure 2-12) in three decades (Vermont Department of Forests, Parks & Recreation, 2021). LDD is an invasive pest that was introduced to North America in 1869. LDD caterpillars prefer feeding on oak leaves but will eat the leaves of many other trees, including maples, birches, and even pines when their favorite host is not available (Davidson et al., 1999). The caterpillars in 2021 were prolific enough that they caught the notice of many Vermonters (Robinson, 2021). In addition to defoliating many trees, LDD caterpillars can cause uncomfortable rashes for some people who come into contact with them (Kikuchi et al., 2012).

Populations of LDD, though present at low levels each year, are usually kept in check by a fungus that needs wet conditions to thrive. Vermont's recent drought conditions have prevented the fungus from carrying out its population control, leading to the 2021 LDD explosion. The next few years could see more high levels of LDD if dry periods continue. Though one year of LDD defoliation is not catastrophic for trees (Figure 2-13), two or more consecutive years could be deadly (Vermont Department of Forests, Parks & Recreation, 2021). Especially in combination with other stressors like drought, LDD is a serious threat to Vermont's forests. Climate change is causing more variable and extreme precipitation changes. If more drought is in the future, then more LDD destruction certainly is too (Davidson et al., 1999). Vermonters should read the advice from the Vermont Department of Forests, Parks, and Recreation to control the spread of LDD in future years (Vermont Department of Forests, Parks & Recreation, 2021).

Figure 2-12: An LDD moth caterpillar. Photo: Charles C, 2011

Figure 2-13: Heavy defoliation caused by LDD in Pennsylvania during a 2007 outbreak. Photo: Dhalusa, 2007

1.16.2 Abiotic Disturbances

Although large-magnitude disturbances such as windstorms and ice storms are historically rare in Vermont, these extreme events are projected to increase in frequency and severity due to climate change (Reidmiller et al., 2018). Models indicate that such events will occur with increasing stochasticity (unpredictability), making specific future impacts difficult to forecast (Janowiak et al., 2018). Abiotic disturbances have a range of impacts on Vermont's forests, from tree mortality to altered forest structure to changing soil conditions.

Box 2.4: Effects of Future Precipitation Scenarios on Forest Regeneration

Written by Peter Clark, University of Vermont

Climate change has already increased precipitation and altered the intensity of precipitation in Vermont, trends that are expected to continue (see Climate Change in Vermont chapter). In the northeastern United States, heavy precipitation events (>1 inch per day) punctuated by long periods of drying are already more common and are projected to increase throughout the twenty-first century with broadscale consequences on forest ecosystem function, composition, and the delivery of ecosystem services.

A recent scientific experiment was conducted in the University of Vermont's Jericho Research Forest to understand the effects of future precipitation changes on forest regeneration (Clark and D'Amato, 2019). This study focused on recently harvested areas that are now forest gaps (Figure 2-14). Within forest gaps, seedling germination and survival was measured with experimental treatments controlling precipitation. Replicated precipitation manipulation experiments were installed for a series of monitoring plots. Experimental treatments manipulated water input to simulate historic precipitation conditions in some plots and scenarios of future precipitation in others. The precipitation manipulations included total precipitation as well as different combinations of rainfall frequency and heavy precipitation events, creating extreme short- and long-term drying and wetting conditions.

This study showed that seedling survival was controlled by precipitation treatment, functional traits (e.g., seed mass), and planting microsite. While the role of climate in seedling survival has been well described in scientific literature (e.g., Fisichelli et al., 2014), this study showed that the survival response to precipitation was largely controlled by species-specific functional attributes. For instance, species with smaller-massed seeds (i.e., birches, pines, maples, and hemlock) were significantly affected by differences in precipitation treatments, but larger massed species (i.e., oaks, hickories, beech, and chestnut) were unaffected.

These findings suggest that heavy precipitation events will not be enough to offset moisture deficits during prolonged dry periods in the future when it comes to seedling germination and survival. Future forest regeneration will favor species adapted to extended drying. Precipitation played an important role in seedling survival, but this study also showed that seedbed microsite conditions (e.g., mixed scarified > unmodified forest soils) were over twice as important in determining seedling survival than the precipitation regimes in the study. The implications of this work suggest that interacting effects of climate, species functional traits, and microsite conditions via disturbance or management will influence many aspects of the regeneration of future northeastern forests.

Figure 2-14: Experimental plots (elevated wooden rectangles) within a forest gap with controlled precipitation (exclusion, watering) used in the forest regeneration precipitation manipulation experiment at the University of Vermont Jericho Research Forest. Photo: Peter Clark

1.17 MANAGEMENT AND MITIGATION

Vermont’s forests are an important economic and ecological resource: the forest products industry generates approximately $1.4 billion in revenue and supports 10,500 jobs annually (Vermont Sustainable Jobs Fund, 2017). Forest management in Vermont creates jobs, provides essential local wood and non-wood forest products, and protects forest health. Vermont’s forests currently store approximately 1,730 million metric tons of carbon dioxide equivalent (MMt CO_2e). Since 1990, Vermont’s forests have removed or sequestered approximately 5.5 MMt CO_2e per year from the atmosphere (Kosiba, 2021a).

Forest management occurs along a spectrum ranging from intensive harvesting activities to passive management and not harvesting trees. Decisions along this spectrum seek to meet goals of biodiversity, carbon sequestration and storage, periodic income, timber and non-timber forest product output, recreation, aesthetics, forest health, and global change adaptation. Generally, any management decision requires calculating tradeoffs between the above objectives. Passive management does not necessarily mean that a forest will remain undisturbed in the long term, but it does mean that the next disturbance is less likely to be directly caused by humans (see Disturbance section).

Climate change poses a threat to forest management operations, as shorter, warmer winters make it harder to carry out management activities typically conducted when the ground is frozen. These new challenges have cascading negative effects on rural economies and management actions that would benefit forest climate change adaptation, response to forest disturbances, wildlife habitat, and forest productivity.

Globally, forest management with a primary or solitary goal of carbon storage or sequestration is becoming popular as a climate mitigation solution, but management for a singular goal may have detrimental effects on forest economies, biodiversity, and forest health at the expense of other forest processes and ecosystem services. For example, a forest that is managed passively may have higher carbon stocks (i.e., carbon in aboveground biomass) than a recently harvested forest, but it could be sequestering carbon at a lower rate (i.e., lower NPP) and due to past human activity, lack the structural and functional complexity that provides it resistance or resilience to climate change (e.g., Bradford and D'Amato, 2012). Further, owning land costs money (e.g., landowners must pay taxes, maintenance of access to the land), and periodic timber harvests provide income to pay these expenses, incentivizing landowners to keep forests as forests. Wilderness conservation easements or payments for carbon storage (see Mitigation section) often do not provide the same sort of periodic long-term income (Graves et al., 2020).

1.17.1 Impacts on Length of Logging Season

The logging industry in Vermont historically has been dependent on operations that take place in the winter on frozen ground or on snowpack atop frozen ground, as loggers work to minimize soil erosion and potential damage to tree root systems at sensitive sites. Warmer nighttime temperatures in December and January (see Climate Change in Vermont chapter) mean that the ground is not freezing fully as early as it used to, and it is thawing earlier in the spring, shortening the logging season, (Figure 2-15; Contosta et al., 2019). Vermont's freeze-free period has increased by three weeks since 1960 (see Climate Change in Vermont chapter). Further, snow often falls before the ground is fully frozen, insulating the ground from frost and potentially leading to winters where the ground never fully freezes (Rittenhouse and Rissman, 2015). These conditions reduce the number of operable days for logging contractors.

Dry summer months offer the second major logging season in the state. However, increased rainfall in June and August, often falling in the form of heavy precipitation events (greater than one inch), saturates the soils with water. This limits loggers' ability to operate during these months without causing significant ecological damage or physical damage to infrastructure and machinery.

Poor logging conditions also lead to a need for longer contracts; rather than finishing jobs in six months to one year, contracts often need to last two full years to ensure enough operable days. This can disincentivize landowners to take on active management activities and mean that logging contractors must spread their operations across many sites based on weather and market conditions.

1.17.2 Impacts on Logging Occupation

One way that logging contractors improve their ability to operate in poor conditions is to expand or alter their equipment inventory. It often becomes necessary for contractors to own a bulldozer or excavator to protect sites, adding to costs when there is already a low profit margin (Kuloglu et al., 2019). Different logging equipment choices are needed for different sites and conditions, so operators are forced to make tough decisions about what might serve them best in the future. Sustained or higher costs combined with fewer days available to work means that fewer logging contractors can maintain their businesses. Between 2002 and 2016 there was a 36% decrease in jobs in the forest products industry and 11% decrease in forest products businesses (Vermont Sustainable Jobs Fund, 2017). These changes are not solely climate driven, as the 2008 recession played a large role, but highlight a trend that is and will be exacerbated by climate change.

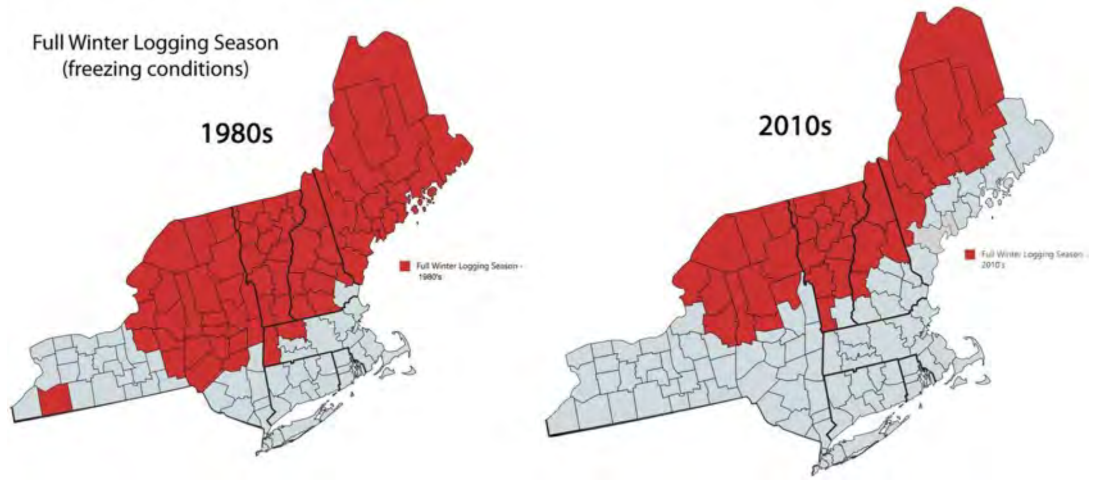


Figure 2-15: Changes in length of winter logging season in the northeastern United States from the 1980s to the 2010s (Bick et al., 20190

1.17.3 Impacts and Adaptation of Sawmills

As climate change limits timber harvest, it also threatens the ability of sawmills to procure enough wood of sufficient quality in a timely and consistent manner to remain solvent. Reduced operation time for logging contractors and low capacity for timber harvesting mean that sawmills may struggle to bring in enough wood to keep their operational rate consistent. Historically, sawmills were able to stockpile logs through the winter season, leaving them with enough wood to saw during other seasons (Bick et al., 2019). A shorter winter harvest season means a need to store more logs whenever they can be cut, which may be restricted by lack of storage space and the fact that cut logs have a limited period of viability before they must be sawn.

Sawmills may also be restricted by the costs and carbon emissions associated with transport of logs, lumber, pulp, and sawdust. Exacerbating these limitations, forest products are often moved outside of Vermont, and poor road conditions, such as those caused by icy conditions or winter thaws, further increase costs. Even though regional mills are not vertically integrated (generally, they do not own the land that is the source of their logs), they may need to work on investing in on-the-ground operations by supporting suppliers. Sawmill support of logging operations may take the form of funding and lending portable skidder bridges, maintaining flexibility in wood delivery timing, providing support for equipment upgrades, preferentially purchasing wood from operators with equipment that has a lighter touch on the land, and providing financial support for site maintenance activities such as adding gravel and grading roads.

1.17.4 Impacts on Wood Markets

Wood prices, including lumber, are influenced by harvesting conditions, mill operations, and markets. In Vermont, sugar maple and red oak tend to fetch the highest stumpage prices (price paid for standing timber; Figure 2-16). Prices can be volatile, and markets may change suddenly, as evidenced by across-the-board price reductions in 2020 at the start of the COVID-19 pandemic. Demand for wood drives the price that a sawmill can charge for lumber, but site accessibility, sawmill capacity, and weather conditions influence how much a landowner can expect to be paid for their standing timber. This disconnect makes it hard to predict how future prices for both standing timber and processed lumber might change, though limits to site access are likely to reduce the dollar value paid to a landowner. Species like sugar maple and ash tend to grow in sites that are richer and moister and more sensitive to marginal operating conditions, while oak trees often dominate on dry sites. Oaks are at the northern edge of their range in Vermont and are more commonly harvested in the southern part of the state.

Sale of low-grade wood products for pulp, firewood, pellets, and biomass provides source material for essential wood outputs for home heating and paper production and subsidizes forest management operations that improve forest health and timber quality. Price and demand of these low-grade products are dependent on mill capacity, and the closure of a large pulp mill in Maine in 2020 is expected to limit the market for these materials.

Wood prices are variable even absent climate change. Individual tree species fall in and out of popular favor, housing markets fluctuate, and markets for low-grade products change based on fossil fuel prices and policy change (e.g., timber price drop after 2008 recession, price increase under 2017 export tariffs; Figure 2-17). Wood markets in Vermont do not operate in a vacuum; logs are exported, and wood products are imported. A more detailed prediction of future market changes would be a fool's errand; however, a portfolio approach of managing for healthy trees regardless of species presents a way to buffer against changes in an unknown future.

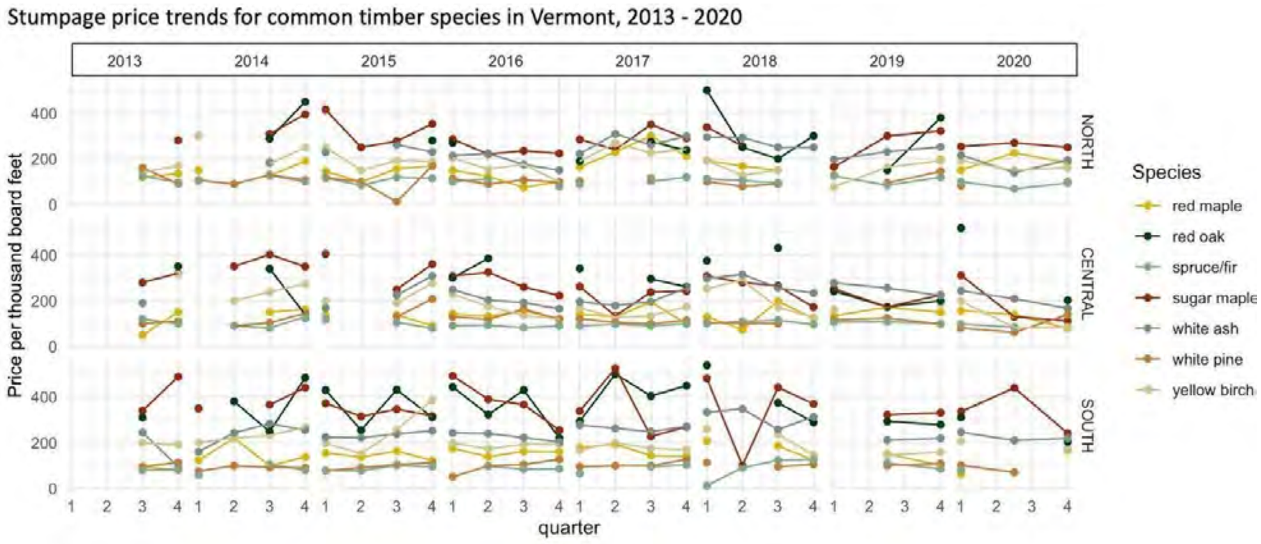


Figure 2-16: Stumpage price (price paid for standing timber) for common sawtimber species across Vermont

Note: The values represented here are intended to be indicators of relative stumpage value and used for guidance only, as many are based off one or two sales. They are not statistically valid and meant to only represent general trends.
North = Caledonia, Essex, Franklin, Grand Isle, Lamoille, Orleans; Central = Addison, Chittenden, Orange, Washington; South = Bennington, Rutland, Windham, Windsor, Source: VT FPR

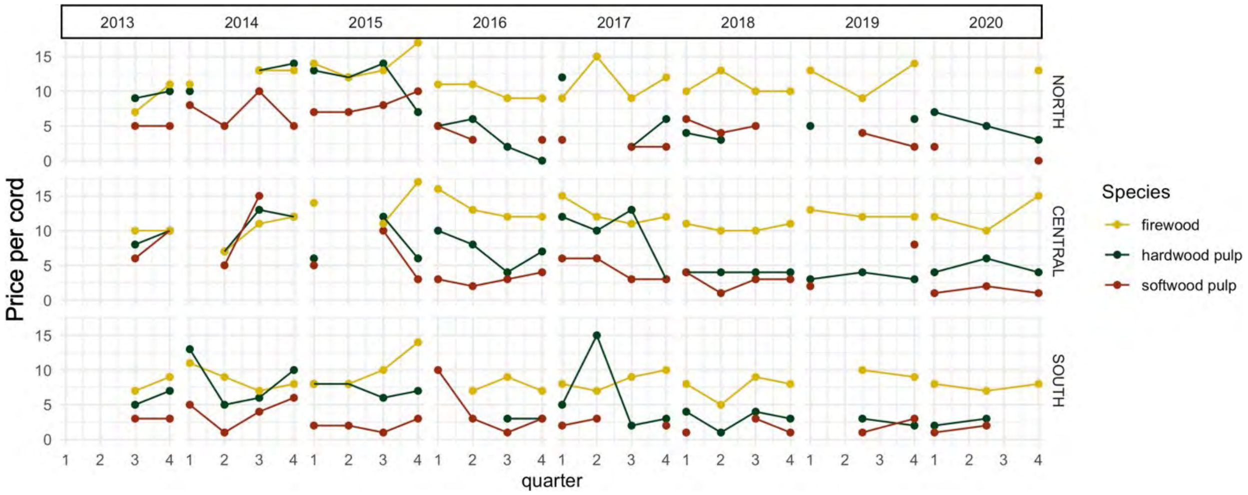


Figure 2-17: Price trends for low-grade wood products across Vermont. Source: VT FPR

Note: The values represented here are intended to be indicators of relative stumpage value and used for guidance only, as many are based off one or two sales. They are not statistically valid and meant to only represent general trends.
North = Caledonia, Essex, Franklin, Grand Isle, Lamoille, Orleans; Central = Addison, Chittenden, Orange, Washington; South = Bennington, Rutland, Windham, Windsor Source: VT FPR.

1.17.5 Infrastructure Costs

As precipitation and winter temperatures increase, road improvements are often needed for operators to move wood on harvest sites and along roads to mills. On harvest sites, this means more time and resources spent on road construction, increased need for gravel to stabilize roads, and more robust structures to manage water flow. On paved roads where heavy log trucks travel to mills, water flow structures are likely to need improvement to handle increased run-off and avoid damages to roads.

The United States Forest Service has adopted stream-simulation design, or drainage structures that retain the natural stream bottom rather than round culverts, as the preferred approach in their forest road systems. In the Green Mountain National Forest, Vermont identified culverts that were replaced with stream-simulation design before Tropical Storm Irene occurred (Gillespie et al., 2014) The difference in cost between using the prior design and the stream-simulation design varied from 9 to 22%. Even more noteworthy is the difference between the cost of the alternative design (Table 2-4a) and flood damages to culverts like the prior designs that were not replaced before the storm (Table 2-4b): despite higher initial costs to install stream-simulation design drainage, the preferred design avoids a much higher road repair cost after an extreme precipitation event.

Table 2-4: Culvert costs on Green Mountain National Forest (a and b) (Gillespie et al., 2014)

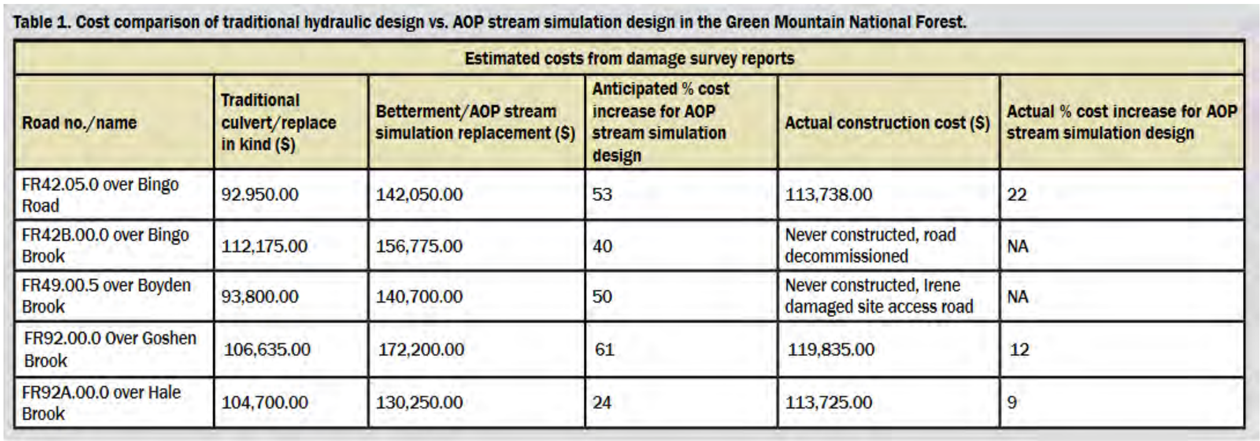


Table 1. Cost comparison of traditional hydraulic design vs. AOP stream simulation design in the Green Mountain National Forest.

Estimated costs from damage survey reports					
Road no./name	**Traditional culvert/replace in kind ($)**	**Betterment/AOP stream simulation replacement ($)**	**Anticipated % cost increase for AOP stream simulation design**	**Actual construction cost ($)**	**Actual % cost increase for AOP stream simulation design**
FR42.05.0 over Bingo Road	92.950.00	142,050.00	53	113,738.00	22
FR42B.00.0 over Bingo Brook	112,175.00	156,775.00	40	Never constructed, road decommissioned	NA
FR49.00.5 over Boyden Brook	93,800.00	140,700.00	50	Never constructed, Irene damaged site access road	NA
FR92.00.0 Over Goshen Brook	106,635.00	172,200.00	61	119,835.00	12
FR92A.00.0 over Hale Brook	104,700.00	130,250.00	24	113,725.00	9

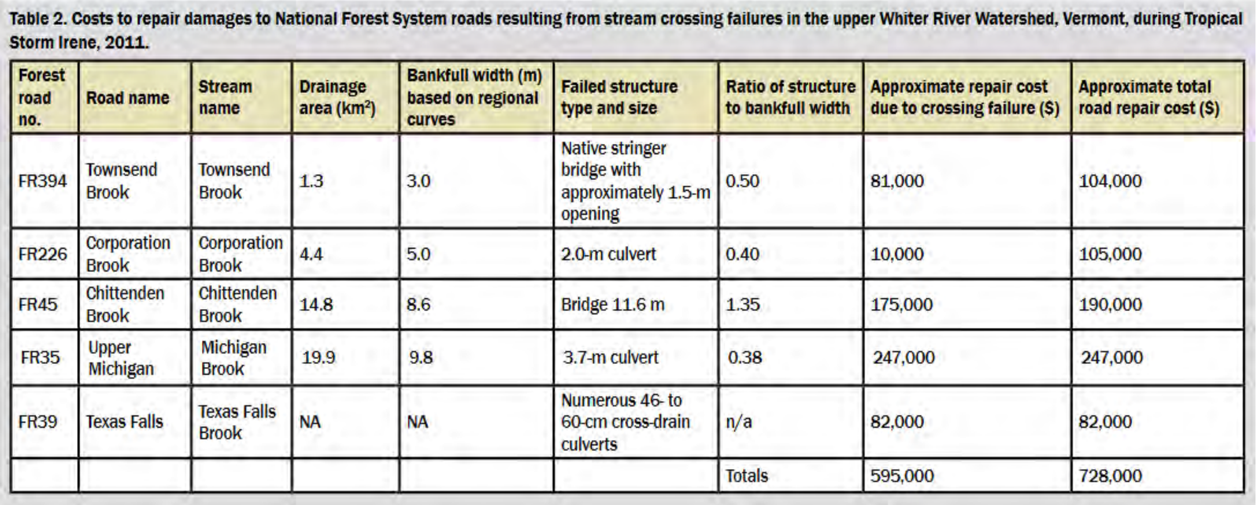


Table 2. Costs to repair damages to National Forest System roads resulting from stream crossing failures in the upper Whiter River Watershed, Vermont, during Tropical Storm Irene, 2011.

Forest road no.	**Road name**	**Stream name**	**Drainage area (km^2)**	**Bankfull width (m) based on regional curves**	**Failed structure type and size**	**Ratio of structure to bankfull width**	**Approximate repair cost due to crossing failure ($)**	**Approximate total road repair cost ($)**
FR394	Townsend Brook	Townsend Brook	1.3	3.0	Native stringer bridge with approximately 1.5-m opening	0.50	81,000	104,000
FR226	Corporation Brook	Corporation Brook	4.4	5.0	2.0-m culvert	0.40	10,000	105,000
FR45	Chittenden Brook	Chittenden Brook	14.8	8.6	Bridge 11.6 m	1.35	175,000	190,000
FR35	Upper Michigan	Michigan Brook	19.9	9.8	3.7-m culvert	0.38	247,000	247,000
FR39	Texas Falls	Texas Falls Brook	NA	NA	Numerous 46- to 60-cm cross-drain culverts	n/a	82,000	82,000
						Totals	595,000	728,000

Box 2.5: Testing Adaptation Methods for Forest Management Operations

Climate change is expected to limit operability for carrying out forest management activities. Concerns revolve around longer mud seasons in the spring and fall and warmer winters with less frozen ground and snow cover that may not safely freeze roads and stream crossings, thereby limiting erosion. A joint project between Atlas Timberlands and Vermont Land Trust (Climate Change Response Framework, 2020) tested options to keep operating logging equipment in the midst of climate change by focusing more on preventing problems than fixing them. (Note: This land has since changed hands and the project has ended).

Option 1: Changing equipment. A shift from skidding wood to cut-to-length systems limits impact to the ground and provides incentive to retain slash in the woods. The downside is the expense to change equipment; this change requires a cut-to-length harvester and forwarder.

Option 2: Cut in summer and minimize impacts via improved bridges and other road construction. A greater investment in road construction and portable skidder bridges makes summer logging more feasible (and summer drought could help this), but extra costs are incurred.

Option 3: Pre-manage roads. Construction of smaller water bars (earthen drainage structures that direct water off roads to prevent erosion) before close-out (as opposed to waiting until close-out to install full water bars) and brushing in roads before they get muddy are both ways to protect roads and increase the number of workdays possible at minimal cost.

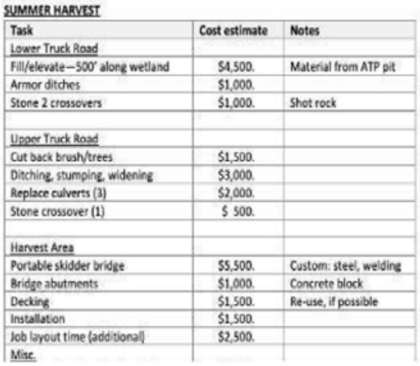
Outcomes: This case study illustrates that it is cheaper and easier to log during a cold winter (Table 2-5), though, unfortunately, this is becoming less possible. Logging in other seasons is feasible but may take a greater financial investment. The options discussed in this section can increase operability but have limitations, including on private land, where closed logging roads are often used for footpaths, stacked brush on roads and water bars diminish landowner use of the roads and post-harvest satisfaction. Changing equipment requires education, financial investment, and buy-in by loggers that these changes will ultimately benefit their businesses. Options that will help logging contractors adapt include nimbleness (i.e., ability to move between jobs based on site conditions) and purchase of site management equipment (i.e., bulldozers or excavators), both of which come with increased costs. Cost-sharing of equipment and resources like portable bridges may help reduce the cost of these activities.

For forest managers, adaptation options will include a) writing logging contracts to span a longer time to ensure enough time with good operating conditions and b) separating road-building contracts from timber contracts to ensure that road upgrades can be carried out. Determining the best adaptation methods will require cooperation between foresters and logging contractors, as they are on the ground managing site conditions. Adaptation actions by logging contractors will need to be incentivized and supported so that these contractors can adapt their practices to new conditions.

Table 2-5: Estimated costs of shifting from winter to summer harvesting on Atlas Timberlands Operational Adaptation Project

WINTER HARVEST

Task	Cost estimate	Notes
Lower Truck Road		
Fill/elevate—500' along wetland	$4,500.	Material from ATP pit
Armor ditches	$1,000.	
Stone 2 crossovers	$1,000.	Shot rock
Upper Truck Road		
Cut back brush/trees	$1,500.	
Ditching, stumping, widening	$3,000.	
Replace culverts (3)	$2,000.	
Stone crossover (1)	$ 500.	
Misc.		
Skid road construction (main)	$500.	
Plowing	$500.	
TOTAL (Winter)	**$14,500.**	



SUMMER HARVEST

Task	Cost estimate	Notes
Lower Truck Road		
Fill/elevate—500' along wetland	$4,500.	Material from ATP pit
Armor ditches	$1,000.	
Stone 2 crossovers	$1,000.	Shot rock
Upper Truck Road		
Cut back brush/trees	$1,500.	
Ditching, stumping, widening	$3,000.	
Replace culverts (3)	$2,000.	
Stone crossover (1)	$ 500.	
Harvest Area		
Portable skidder bridge	$5,500.	Custom: steel, welding
Bridge abutments	$1,000.	Concrete block
Decking	$1,500.	Re-use, if possible
Installation	$1,500.	
Job layout time (additional)	$2,500.	
Misc.		

1.18 FOREST MANAGEMENT CHALLENGES AND OPPORTUNITIES

1.18.1 Ability to Carry Out Silvicultural Operations

Management for wood products, non-timber forest products, wildlife habitat, recreation, and climate mitigation are all dependent on the ability to carry out silviculture, or the planning of goal-based forest management activities around the ecology of the forest and the species that occupy it. Limits to operability in forests may lead to struggles to reach silvicultural goals. For example, sugar maple, a dominant and desired tree in Vermont, regenerates best through leaf litter on the forest floor. Harvesting in snowy conditions leaves the forest floor undisturbed, but as winter harvest becomes more difficult and less common, more ground scarification can occur during harvest, benefitting the regeneration of other species. Beech trees, already impacted by beech bark disease (see disturbance subsection; Cale et al., 2015) will aggressively root sprout with ground disturbance, and forests containing high amounts of diseased beech are often intentionally managed in the winter. The loss of winter logging may have cascading effects on forests, increasing beech sprouting, which will ultimately limit the regeneration of other desired tree species such as sugar maple.

More generally, stressors related to climate change and globalization (e.g., spread of invasives) will require forest management action to aid with ecosystem adaptation. Economic impacts that reduce operator availability, close mills, discourage forest products as a career path, or constrain forest management limit the ability for foresters, who are trained and able to manage forests for adaptation, to carry out management actions that can benefit the forests and rural communities and provide local wood to Vermonters. Wood product consumption tends to remain fairly consistent, so if not sourced locally then wood is being harvested elsewhere, potentially in a location with fewer environmental regulations, greater costs, and increased carbon emissions from longer transportation routes (Berlik et al., 2002).

1.18.2 Active Management vs. Passive Management

As climate change mitigation becomes more of a policy priority, the value of forests as a natural carbon sink is increasingly recognized. This has led to a flurry of recent research seeking to understand how much carbon is stored by forests and which forest types, forest ages, and management approaches are best for climate mitigation. The science of forest carbon is in a state of flux, as new measurements and methods arise to understand carbon dynamics and climate mitigation potential. Passive management, or the decision to not carry out management activities in a forest, has been put forth as the way to maximize forest carbon storage, though not necessarily sequestration (Luyssaert et al., 2008), but recent research indicates that old or passively managed forests may not be storing as much carbon as previously suspected (Gundersen et al., 2021). Additionally, good, active forest management can lead to large healthy trees that, when harvested, convert to carbon storage in durable wood products; this can be a long-term (100-year) solution for keeping carbon out of the atmosphere while still realizing a broad suite of services from the forest (Dugan et al., 2021). Prioritizing the mitigation value of forests by choosing a passive management approach has both positive and negative effects; no one management solution is best for all forests. Funding for carbon credits (see below) can support conservation of forest land, insurance from land use change, and good business practices. High levels of carbon sequestration in forests can offset the carbon emitted by fossil fuel use, but this process can be only one part of climate mitigation and must go hand in hand with reduction of CO2 emissions. Depending on the scale employed, passive management with the sole emphasis of maximizing carbon storage creates the potential to minimize other ecosystem goods and services provided by forests, such as wildlife habitat, wood products, non-timber forest products, water filtration, and recreation.

One point of confusion is the differences between carbon sequestration and carbon storage. Sequestration describes the amount of carbon that is actively being removed from the atmosphere, while storage is the amount of carbon that is being held in trees and forest soils. Sequestration and storage have different relationships with stages of forest development: while older forests store more carbon, younger forests tend to sequester more carbon (Figure

2-18). While some research indicates that old forests store a significant volume of carbon, forests are dynamic systems, and old forests do not remain in a steady state. As a result of past land use, Vermont's forests are predominantly in the eighty to hundred-year age class (see Structure and Composition subsection). This uniformity in age class means that a greater portion of the forests are vulnerable to similar types of disturbances, threatening their ability to store carbon and opening the possibility that vast portions of the forest could revert to a younger state simultaneously, upsetting the current carbon dynamics of Vermont's forests.

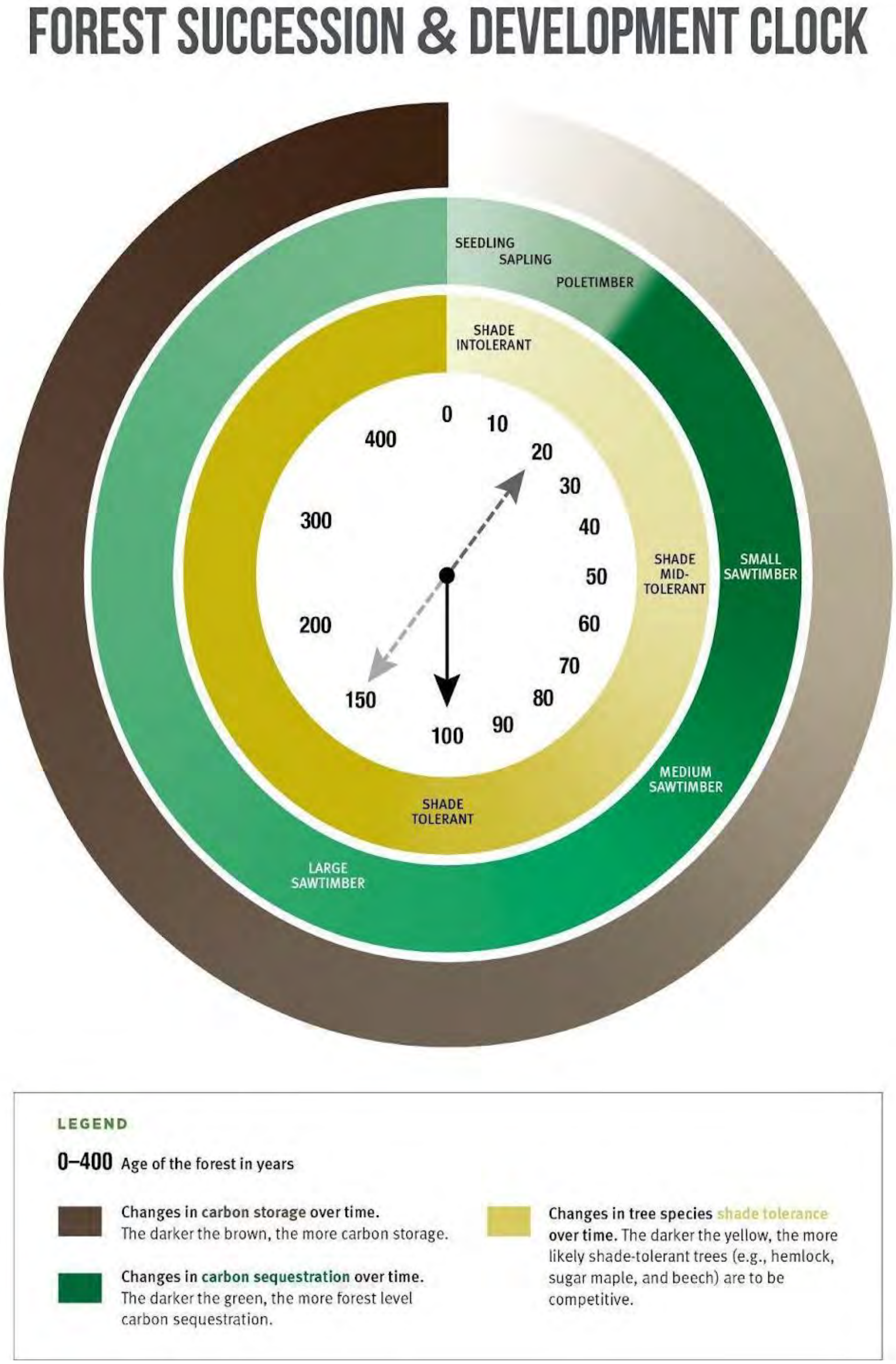


Figure 2-18: Rates of carbon sequestration and storage throughout forest stand development (Catanzaro and D'Amato, 2019)

1.18.3 Land Use Change

Written by Jamey Fidel, General Counsel, Forest and Wildlife Program Director, Vermont Natural Resources Council.

Vermont is the fourth most heavily forested state in the country, and while approximately 74% of the state is covered by forests, forests are declining in extent on an annual basis (USDA Forest Service, 2020). While it is extremely hard to pinpoint the exact amount of forest loss, according to the Forest Service, approximately 14,207 acres of forest land are being converted to non-forest every year (USDA Forest Service, 2020) After factoring in land that may revert to forest, at this rate a net of over 300,000 acres of forestland may be converted to non-forest by 2050 (USDA Forest Service, 2019).

As forests become more compromised by development and urbanization, their ability to remain healthy and provide ecosystem services, such as sequestering and storing carbon, will be diminished. For example, a Forest Carbon Assessment documented that the total annual uptake of carbon was less in 2015 (the end of the period of analysis) than in previous decades, in part due to declining acres of forest land (Schultz et al., 2017). A more recent forest carbon inventory confirmed that land use change has resulted in net emissions in Vermont, which is concerning because forest land that is converted not only emits stored carbon, but it also reduces future forest carbon sequestration (Kosiba, 2021a).

As large undeveloped forests are broken into smaller and smaller parcels from subdivision, forest management becomes more challenging, and the relationships between parcel size and forest owner behaviors have important implications for timber supply, resiliency, restoration, and keeping forests as forests (Butler et al., 2021). Data gleaned from the Grand List in Vermont highlights that undeveloped woodland as a land category decreased significantly from 2004 to 2016, while residential acreage increased by almost 162,670 acres (Fidel et al., 2018). During the same period, the amount of land in parcels 50 acres or larger declined by about 110,300 acres, while the number of parcels under 50 acres in size with new houses increased by 20,747 parcels (Fidel et al., 2018). This highlights an increasing trend in Vermont: undeveloped forest land is being converted to residential development with houses and associated infrastructure, and smaller parcels are being created through the fragmentation and parcelization of forestland from subdivision and development. Left unaddressed, these trends will limit the ability of forests to remain resilient and provide vital services to mitigate the impacts of climate change.

1.18.4 Carbon Markets

Vermont's Department of Forests, Parks, and Recreation has created comprehensive reports explaining forest carbon, the carbon market, and its status and relevance in Vermont (Kosiba, 2021b). Here, carbon offsets as a forest management opportunity for Vermont's landowners are summarized.

Forest carbon offsets aim to reduce global CO_2 emissions by taking advantage of forests' ability to sequester and store carbon. Carbon offsets put a market value on sequestration or storage to make up for emissions of CO_2 in cases where CO_2 reduction is impossible or undesirable. Carbon offsets allow companies or individuals to offset their own carbon emissions by paying to guarantee that carbon elsewhere is *sequestered* (actively removed from the atmosphere and stored in another form or location) or *stored* (remaining in another form or location, preventing its release back to the atmosphere). The key to effective carbon offsets is that the payment is responsible for carbon sequestration or storage that would not have happened or continued without it. Because forests are excellent at storing and sequestering carbon, they are an opportunity for CO_2 emitters to offset their climate impacts. And because forests cover much of Vermont, the growing market for carbon offsets is an economic opportunity for Vermont's forest landowners.

Carbon offsets, also known as carbon credits, are treated as a currency in units of the equivalent of 1 metric ton of CO_2. A metric ton is about the amount of CO_2 emitted by an American car driven regularly for two-and-a-half months or the amount of carbon sequestered by forty-six mature trees in a year (US EPA, 2015). Carbon offsets are bought and sold on carbon markets or registries, of which there are several, each with somewhat different restrictions and requirements. Some carbon markets are regulatory, used as a tool to help large emitters in states like California meet state CO_2 emission guidelines, while others are voluntary, where companies and individuals choose to pay to offset their emissions. Over the past several decades, an industry has grown around these carbon markets, so there are now organizations and consultants—such as carbon developers and third-party verifiers—engaging in every step of the process that facilitate these transactions.

Forest carbon offset projects fall into one of three categories: 1) afforestation or reforestation (tree planting), 2) avoided conversion (blocking the clearing of already-forested land), and 3) improved forest management (shifting management practices to allow an existing forest to store and/or sequester more carbon than before). Improved forest management is the most relevant to Vermont's forest landowners. Through a variety of management techniques, both active and passive, forests are intentionally managed to maintain their carbon storage at or above an agreed-upon level.

Two key components of carbon offset projects are *permanence* and *additionality*. *Permanence* means carbon must be continually stored for the duration of the project's contract, often from 40 to 100 years, and the carbon stored must remain above and beyond the amount that is stored under a "business as usual" scenario, which is typically benchmarked at a baseline year. *Additionality* is the difference between the increased carbon stored in the offset-insured forest and the baseline of carbon stored without the offset incentive. Determining baselines for forest carbon offset projects can be complicated, and regulations vary among carbon markets. Defining the baseline for a carbon offset project depends on a specific property's circumstances, including legal encumbrances (i.e., easements or deed restrictions) and harvesting regulations. For example, a forest previously protected by a "Forever Wild" conservation easement with no logging allowed may not qualify for a carbon offset project; as the forest is already guaranteed to remain unharvested, there is no additionality possible through an improved forest management project.

However, forest carbon offset projects are compatible with existing programs in other ways. Protecting a forest with a conservation easement at the same time it enters the carbon market can help ensure the permanence of carbon-centric management of the parcel. Forests enrolled in Vermont's popular Use Value Appraisal (or Current Use) program, which provides a tax benefit for actively managed forestland, may also enter a carbon offset project, provided the requirements of both programs continue to be met.

Since carbon markets are varied and evolving, contacting a carbon developer is the best way for interested landowners to learn about the process and whether it may be right for them. The most established carbon registries typically deal with large forest parcels (>2,000 acres), but new and emerging companies are extending this opportunity to smaller forest landowners. Under the right circumstances, projects that aggregate many small landholdings may be appropriate to join the carbon market (see Box 2.6). Small landowners may also benefit from emerging practice-based carbon programs such as the Family Forest Carbon Program being developed by the American Forest Foundation and The Nature Conservancy.

Box 2.6: Cold Hollow to Canada

Forests provide a multitude of ecosystem benefits including wildlife habitat, improved water and air quality, and recreational and aesthetic benefits to humans. Fragmentation diminishes these benefits. For example, the habitat of some birds that nest in interior forests is greatly reduced when these forests are broken up into smaller patches with more exposed edges and less interior. Therefore, small, privately owned forest parcels pose a challenge to conservation; if one of those parcels is developed, the impacts extend to the surrounding forest as well (Baldwin and Fouch, 2018). Landowner cooperation has other benefits, too: sharing resources, equipment, and services such as management planning contribute to more cohesive management and lower costs for individual forest owners (Kittredge, 2005). Carbon markets are set up to include large forest parcels; programs that work with smaller areas are few and still emerging. At this time, managing small, adjacent forest parcels as an aggregate is beneficial both to the humans and animals who use these forests and to the individual landowners who have more options to enter the carbon market.

Beginning in 2018, the Vermont Land Trust and Cold Hollow to Canada coordinated the aggregation and sale of carbon offsets for the forests of ten private landowners. This cooperative project is the first of its kind in the United States. Individual landowners with properties too small to be lucrative on the existing carbon market worked together with partner organizations to sell carbon offsets as a group for their forested land totaling over 7,500 acres (Hancock, 2020). Although historically, only large forest parcels of thousands of acres were economically viable in the carbon market, the Cold Hollow to Canada project represents a way forward for smaller landowners in Vermont and beyond. By banding together, the connected forests are protected as a unit for at least forty years. And by managing for carbon storage, many other ecosystem benefits result; for example, improved water quality and wildlife habitat are amplified by the larger footprint of this project's carbon-rich forests.

1.19 FOREST ADAPTATION AND MANAGEMENT

Forest adaptation describes the capacity to respond to new or novel conditions. Uncertainty is a recurring theme when it comes to forest adaptation to climate change. Over very long historic time scales (thousands of years or more) forests responded to changing climate conditions and persisted, but climate changes now are happening on the scale of decades, so there is concern that forests may not be able to adapt at that pace. In response, forestry has adopted adaptive management, which includes changing forest management approaches in response to changing local conditions and is driven by research and practitioner action.

Forest adaptation and management can be understood within a matrix of change and response, with approaches laid out along a continuum (Figure 2-19; Millar et al., 2007). In forest adaptation and management, there is not one simple solution; rather, site-specific decisions are made based on local conditions and dynamics, management objectives, and best available knowledge about future change. Adaptation requires embracing uncertainty and figuring out the best options out of those available. In the context of forest adaptation and management, a *resistant* forest remains consistent in structure and function through change, whereas a *resilient* forest accommodates some change but retains the capacity to return to a desired reference condition. A *transition* forest is in the process of adapting to new conditions and eventually may look quite different from what is currently on site, though it still performs similar ecosystem functions.

Adaptive capacity of forests is based on forests' structure, composition, and function; adaptive management approaches target these components of forest ecosystems (Table 2-6). In many cases adaptive management can be carried out in concert with ecological forestry practices, focused on mimicking natural disturbances and processes (D'Amato and Palik, 2020). Forest adaptation is a recent research focus; while it builds on basic ecological concepts, its application is in its early years. Detailed adaptive management approaches are available online from the USDA Forest Service Climate Hubs as an adaptation workbook (NIACS, 2021).

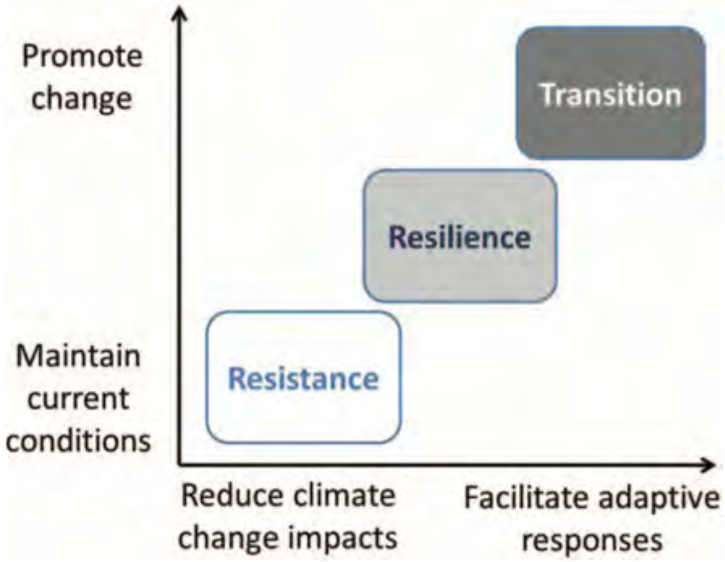


Figure 2-19: Forest Adaptation Spectrum from Nagel et al., 2017

Table 2-6: Examples of adaptive management techniques

Forest Adaptive Management for Climate Change Adaptation			
Tactic	Example	Pros	Cons
Structural retention	Retain large old trees, both living and dead, during timber harvest	“Lifeboat” for species diversity, continuity of forest structures and processes, carbon storage in larger trees, habitat for cavity nesting birds and invertebrates that feed on deadwood	Potential loss of revenue, retaining large trees can create unsafe conditions for operators
Extended rotations	Regenerate forest after 100 years instead of 80 years	Carbon storage, multiple age classes	Potential revenue loss, older forests more vulnerable to disturbance
Increase structural complexity	Intentional creation of horizontal and vertical heterogeneity, tree species, size classes, deadwood decay classes, spatial arrangements	Greater habitat diversity, variety of disturbance recovery pathways	Costs may be limiting, complicated operational layout
Increase functional redundancy and diversity	Include large canopy gaps, retention, and uncut patches to increase diversity of regeneration niches at a stand scale, retain uncommon species	Persistence of rare functional traits through novel disturbance	Complicated operational layout
Increase habitat connectivity	Treat large parcels in a nonuniform manner, plan forest management activities at a landscape scale when possible	Multiple habitat types near each other and connected	Requires cooperation from multiple adjacent landowners
Assisted migration	Plant species from southern New England in gaps created by timber harvest	Forest populated with future climate-adapted species	Efficacy and safety not yet supported by long-term data

Box 2.7: Early Lessons from Adaptation Plantings Aimed at Transitioning Species Composition for Climate Change in the Northeastern United States

Written by Peter Clark, University of Vermont

In 2018, adaptation plantings were installed in harvest gaps in northern hardwood and mixed conifer-hardwood forest across sites in Vermont and New Hampshire as part of the New England installation of the Adaptive Silviculture for Climate Change project (adaptivesilviculture.org). The goal of this experiment was to examine the performance of future-climate adapted tree species from a suite of functional traits (e.g., seed mass, shade tolerance, growth rates) to better understand the relationship between introduced species and contemporary drivers that may control seedling growth and survival.

The future-adapted species ("adaptation plantings") tested included a) "population enrichment" plantings (northern red oak, black cherry, red spruce, white pine, eastern hemlock, and bigtooth aspen), which were generally underrepresented onsite but have ranges that encompassed research sites (Figure 2-20) and b) "assisted range expansion" plantings (black birch (*Betula lenta*), bitternut hickory (*Carya cordiformis*), and American chestnut (*Castanea dentata*), which were currently not onsite but planted with modest advances outside of current range but within future projected habitat range.

Over three growing seasons, 3,152 out of 5,620 total seedling transplants survived (approximately 57%). Seedling growth and survival varied considerably among species, with slight inverse relationships (i.e., some species grew faster, while others had higher survival rates; Figure 2-21). The major factors influencing seedling performance were competition from shrubs and herbaceous plants, species regeneration traits, initial size and health of seedling, and transfer distance from species range.

Sites with strong “ecological memory” in the form of dense natural regeneration were more likely to outcompete the new or novel adaptation plantings; however, sites with heavy deer browse slowed down natural competition, which inadvertently favored many adaption plantings. Moreover, species traits moderated seedling response, such as the ability to root-sprout after winter injury or dieback (e.g., hickory and chestnut), rapid initial growth to outcompete vegetative competition (e.g., aspen, cherry, and pine), energy allocation to roots (e.g., red oak), and inherent deep shade tolerance to persist under competition (e.g., spruce and hemlock).

Population enrichment species performed significantly better than assisted range expansion species, which exhibited more maladaptation, further highlighting the challenges of assisted migration. Additionally, these adaptation plantings experienced extreme climate events, such as a once-in-a-century spring drought during planting and late spring frosts in subsequent years that caused negative consequences on seedling performance that differed by species and across regional sites. Extreme climate events like these are important future climate analogues for conditions that managers will contend with as they consider implementation of adaptation plantings.

Forests in the Northeast are projected to experience profound changes in suitable tree habitats, highlighting the potential importance of adaptation plantings. Assisted migration activities may be necessary to establish future-adapted trees, so the strength of local site competition, adaptive traits, assisted migration distance, and availability of quality and diverse nursery seedling stock will play important roles in determining performance and efficacy of efforts to transition forest composition.

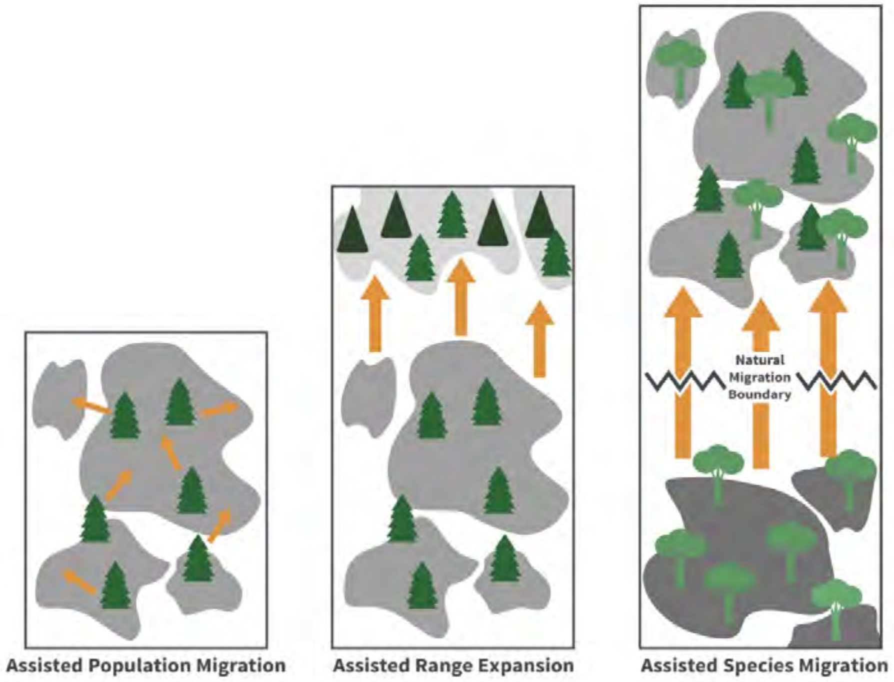


Figure 2-20: Three approaches to assisted migration in tree species (Handler et al., 2018)

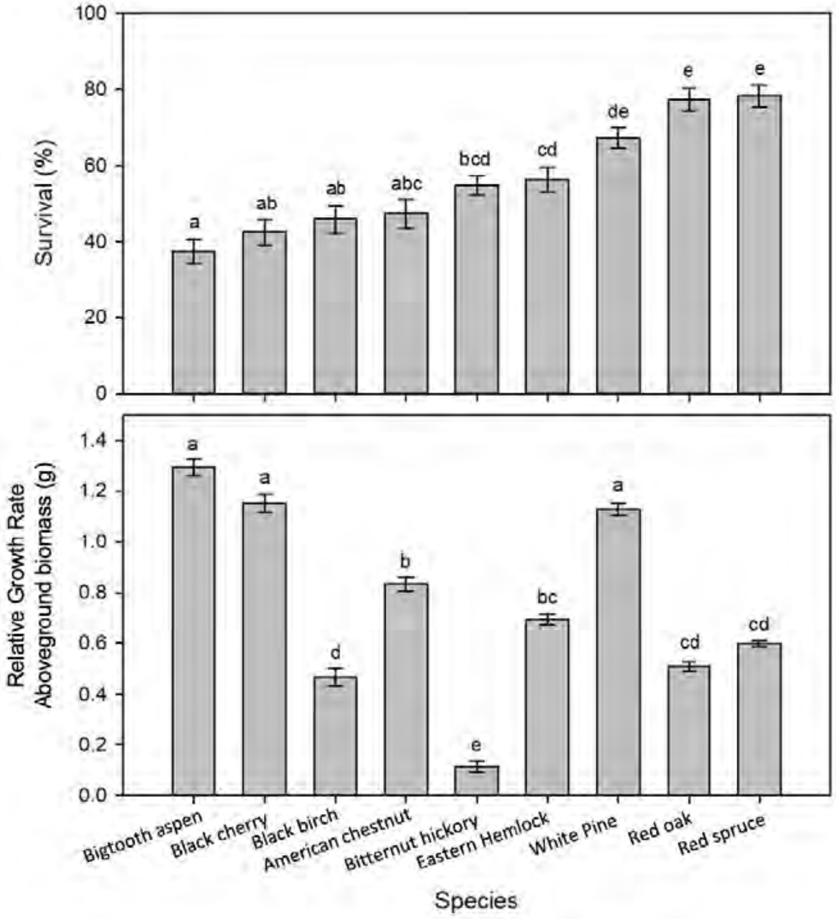


Figure 2-21: Three-year seedling survival (top) and growth (bottom) pooled across multiple silvicultural adaptation planting trials in Vermont and New Hampshire

Note: Growth is measured as the relative annual growth rate in above ground biomass (grams). Letters denote significant differences (α ≤ 0.05)

Box 2.8 Adaptive Silviculture in Response to Emerald Ash Borer and Climate Change

The emerald ash borer (EAB, see Disturbance subsection) will have significant impacts on Vermont forests with ash populations. Forest management may either exacerbate or mitigate impacts. In conjunction with Dartmouth College, University of Vermont researchers are examining adaptive silviculture strategies with the goal to help forests with a significant ash component maintain ecosystem function in the face of this invasive pest and climate change. The research site in Corinth, Vermont is a rich northern hardwood forest dominated by sugar maple with a significant white ash component (Figure 2-22). Silviculture treatments were co-produced with input from multiple interested parties, including the Cowasuk band of Indigenous Abenaki. The silviculture treatments are designed to support a structurally and compositionally complex forest characterized by multiple combinations of species composition and structure. A forest with this structure will have multiple pathways to recover from disturbance, including disturbance created by EAB. In practice, this means creation of five age classes through time, achieved by group selection treatments creating gaps from one-tenth to one-fourth of an acre in size; intentional creation of downed dead wood and cavity trees, achieved by retaining slash on site and leaving uncut large ash trees that are likely to die; planting future climate-adapted species not currently existing on site (e.g., basswood, northern red oak, bitternut hickory, black cherry, bigtooth aspen); and releasing crop trees of basswood, healthy female ash trees, and vigorous, resistant specimens of other species. The treatments will also serve to increase songbird habitat by increasing diversity in vertical and horizontal forest structure, to maintain forest productivity, and to diversify microhabitat conditions to enhance abundance of understory vascular plants, including those of cultural significance to the Cowasuk band of the Abenaki.

Figure 2-22: The adaptive silviculture in response to EAB and climate change research site in Corinth, VT. Photo: Jess Wikle

1.20 URBAN FORESTS AND CLIMATE

There are an estimated 11.9 million trees in Vermont's urban and developed areas (Nowak and Greenfield, 2008). While these areas make up less than 2% of the state's land area, nearly 39% of the Vermont population (243,000 people) lives in a census-defined urbanized area (U.S. Census Bureau, 2012). All trees—whether growing along a street or in a forest—provide critical climate and ecosystem benefits, like carbon sequestration, water infiltration, temperature moderation, erosion control, and pollution abatement. Because of the high population density and lower tree cover in urbanized areas, per-tree ecosystem services in urbanized areas can be higher than in forest settings. Yet because of the amplifying effects of the built environment on temperature and water cycling, along with additional stressors associated with urbanized areas like soil compaction, poor soil fertility, and pollution, urban trees are highly vulnerable to climate change.

1.20.1 Urban Forests and Carbon

Like forest trees, trees growing along roads and in yards, parks, and community forests provide important climate mitigation effects by sequestering and storing atmospheric CO_2 in wood and soil. Unfortunately, there is no standard definition of what constitutes an urban or community forest, so it is difficult to compare mitigation estimates from various sources. Additionally, estimating tree carbon, especially annual sequestration, is challenging and imprecise. It requires modeling a tree's biomass based on the carbon in a reference set of sample trees. These models can be inaccurate for street and yard trees because the growing conditions are highly variable compared to forest-grown reference trees (McHale et al., 2009; McPherson et al., 2016). Finally, to compute the actual climate mitigation effect of a tree, the maintenance inputs should be included (Nowak et al., 2013), and this is often either unknown or highly variable.

Despite these challenges, several sources have estimated the total carbon storage and annual sequestration of Vermont's urban trees. According to these estimates, trees in urbanized areas store about 15 MMt CO_2e (equivalent to the annual emissions from 3.8 coal fired power plants) and sequester 157,000–500,000 Mt CO_2e per year (equivalent to 18,000-60,000 U.S. homes' annual energy use) (Domke et al., 2020; EPA, 2021; Nowak et al., 2013; Zheng et al., 2013). On a per area basis, some estimates suggest that Vermont's street trees sequester CO_2 at a higher annual rate compared to forest trees (Nowak et al., 2013), as urban trees tend to have wider tree crowns, experience less competition from other trees, and have a greater leaf area compared to forest-grown trees. However, urban trees have significantly shorter lifespans and greater maintenance demands, which affect their lifetime carbon storage potential and resultant mitigation benefit (Nowak et al., 2013). After accounting for the greenhouse gas emissions from growing, planting, and maintaining urban trees, one study found that an urban tree must live a minimum of ten years to provide a net positive mitigation benefit (Nowak et al., 2013).

In addition to the direct benefit of sequestering atmospheric CO_2, trees in urbanized areas provide important indirect climate benefits. All trees moderate temperature fluctuations by shading surfaces and transpiring water vapor, but in urban areas this is particularly important because of the urban heat island effect (Millward et al., 2014; US EPA, 2014). A tree's canopy provides shade and wind protection for buildings, which reduces energy needs. This results in lower greenhouse gas emissions and reduced heating and cooling costs (McPherson and Simpson, 1999; US EPA, 2014). Trees also act as green infrastructure, reducing stormwater runoff from extreme rainfall events by transpiring water and keeping soil intact with their roots (Nowak et al., 2020).

1.20.2 Specific Climate Change Impacts on Urban Forests

Trees in urbanized areas experience different and often intensified impacts from climate change because of the built environment. Urban areas may experience hotter and drier climates than interior forests (Fahey et al., 2013). There are more impervious surfaces that cause stormwater runoff (Solecki and Marcotullio, 2013). Under a warmer climate, we may see more ice and windstorms, which can damage trees, infrastructure, and property (Dale et al., 2001; Neumann et al., 2015). Urban trees may be weakened by compounding stresses of heat, drought, extreme weather events, and pests and pathogens, which may not only decrease vigor and growth, but increase mortality. This, in turn, reduces the ability of urban trees to sequester and store carbon (Figure 2-23). A study from Cambridge, Massachusetts found that climate-related changes could result in 58% tree mortality (Foran et al., 2015). Current and future management responses will influence the vulnerability of urban trees and forests.

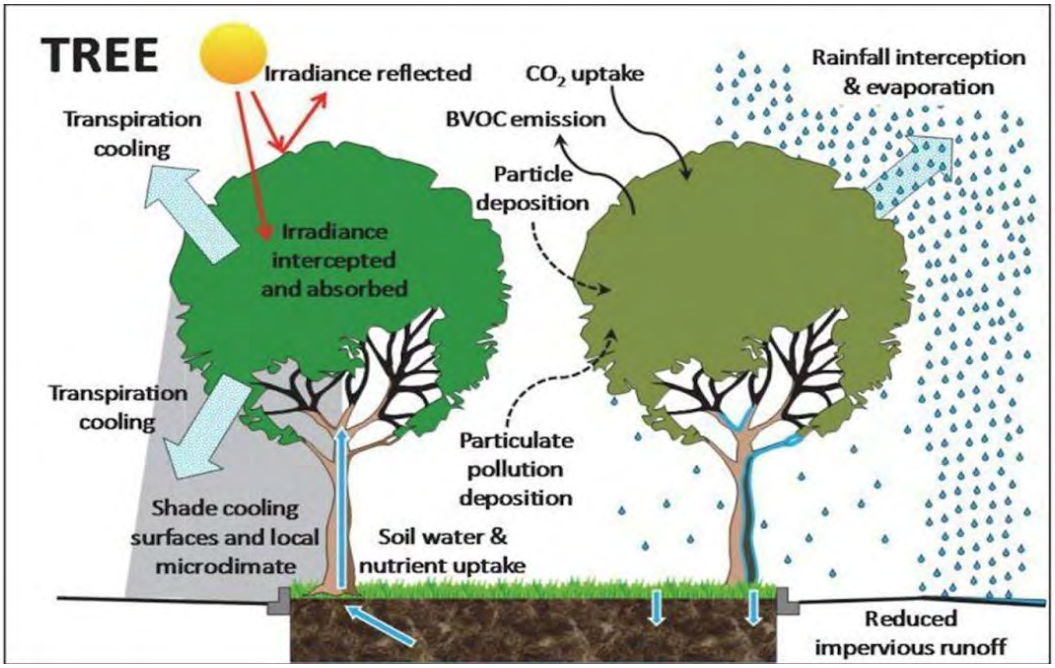


Figure 2-23: Climate change impacts on urban street trees alter benefits provided by those trees. Modified from Livesley et al., 2016

Invasive pests, pathogens, and plants also pose threats to Vermont's urban trees and community forests. Invasive insect infestations—often targeting specific tree species—strengthen the case for planting a diverse and resilient urban forest as they may eliminate entire swaths of urban-tolerant trees. Climate-related stressors on urban trees—such as drought—may increase an individual tree's susceptibility to infestation or disease (Tubby and Webber, 2010) and warmer winter temperatures create conditions for some tree pests and diseases to thrive. Competition from invasive plants—less of a concern for street tree populations but certainly relevant to forested parks—impedes natural regeneration of native forest species and has reverberating impacts on natural communities, wildlife, and the local economies that depend on these wooded landscapes for tourism and recreation (Milanović et al., 2020).

There are numerous examples of the impacts of invasive insects and disease on urban trees. Many of Vermont's downtowns experienced widespread loss of American elm (*Ulmus americana*) in the mid-twentieth century due to Dutch elm disease (*Ophiostoma* spp.). Now many of these same communities are preparing for the loss of ash trees—particularly planted green ash (*Fraxinus pennsylvanica*)—from streets and parks due to the invasive emerald ash borer, which was first detected in Vermont in 2018. According to the Vermont Urban & Community Forestry Program's (VT UCF) inventory of public urban trees (>24,000 trees across thirty municipalities), approximately one out of every six Vermont downtown and neighborhood trees is an ash. Additionally, municipal staff and volunteers in more than forty towns and cities have recorded over 45,000 ash trees along rural roadsides using VT UCF's Rural Roadside Ash Inventory Tool (VT UCF, 2021a).

Together, these stressors add complexity to the already daunting task of selecting and sourcing urban-tolerant tree species for planting and of moving the needle towards diverse species composition in urban areas. Only four Vermont municipalities have an arborist on staff. This means that in most communities, tree planting and maintenance efforts are led by citizen volunteers or are contracted to outside organizations. Vermont's limited number of tree nurseries are challenged with selecting and propagating species that will be successful in an uncertain future. Until recently, there has been little attention to genotypes (genetic adaptation) when breeding trees for planting. Even within a species there is significant variability in physiological response to climate and site factors, such that seed source is an important consideration under a changing climate. Resources to aid these decision-makers are increasingly important to steward long-lived tree species that can provide sustained benefits for urban populations. The US Forest Service's Climate Change Tree Atlas is an example of one such resource that supports strategic selection of tree species that have high adaptive capacity in the face of climate change (Peters et al., 2020).

1.20.3 Adapting Urban Forests

Worldwide, many cities, regions, and even countries are assessing existing canopy cover using advanced spatial analysis tools (e.g., aerial imagery, satellite imagery, LiDAR) and establishing ambitious urban tree canopy (UTC) cover goals as part of climate action plans. In Vermont, the University of Vermont's Spatial Analysis Lab continues to build its database of remote imagery and pioneers UTC work at a national level. The VT UCF program has funded UTC assessments in Montpelier, St. Albans City, Rutland City, and South Burlington, and two UTC assessments for the City of Burlington to assess change over time (VT UCF, 2021b). In concert with UTC goals is the recent proliferation of million and even trillion tree-planting initiatives. This collective recognition of the power and importance of urban forestry is encouraging, but they are only worth engaging in if they are done well. Investment in the proper care of urban and community forest trees is vital. Large, long-lived species that have been maintained for structural integrity will provide the most benefits over time (Nowak et al., 2002).

As Vermont urban and community forestry managers consider the role that trees will play in strengthening communities' resilience to climate change, they must also plan to adapt to climate change. Fortunately, there are resources—many online and free—to support climate change resilience and adaptation efforts. The US Forest Service's Vibrant Cities Lab and Climate Change Resource Center and the Northern Institute of Applied Climate Science's Urban Forestry Climate Change Response Framework support climate change-informed urban forestry planning (NIACS, 2021; USDA Forest Service, 2021) The i-Tree suite of tools quantifies the values provided by trees and aids in planning at multiple scales (i-Tree, 2021) New resources like American Forests' Tree Equity Score Tool and the US Forest's Urban Forest Inventory and Analysis (FIA) program support data-driven strategic tree-planting plans so that all people have access to the vast benefits that tree canopy provides (American Forests, 2021; USDA Forest Service, 2021). Organizations such as City Forest Credits are even engaging in efforts to legitimately fund urban forestry through carbon offsets.

While urban and developed areas cover smaller areas of Vermont than other states in New England, future expansion of developed areas is likely. These expansions could result in conversion of forests and other natural and working lands to developed lands, reducing tree cover and forest regeneration while increasing impervious surfaces. Land use planning with a climate adaptation lens that includes healthy trees and forests will be critical to ensuring resilience to climate change.

Box 2.9: Spotlight on Vermont Urban and Community Forestry Program

The Vermont Urban & Community Forestry Program (VT UCF) was established in 1991 as a collaborative effort between the Vermont Department of Forests, Parks, and Recreation and University of Vermont Extension. The program provides technical, financial, and educational assistance to roughly 100 municipalities each year to support the management and stewardship of these forest resources (Figure 2-24).

Since 2017, the program has given 1,250 free containerized trees to 645 households in seven priority municipalities through a partnership with the Arbor Day Foundation's Community Canopy Program (formerly known as Energy-Saving Trees). The Vermont Department of Health's Climate and Health Program has contributed as a funding partner for multiple years, forging a cross-agency collaboration that recognizes the links between tree canopy cover, public health, and the climate-related services trees provide.

Research from the Climate and Health Program has informed partner selection for VT UCF's Vermont Community Canopy Program with the goal to provide free trees to communities that are most vulnerable to heat-related illness. The Vermont Heat Vulnerability Index draws together seventeen different measures of vulnerability in six different themes: population, socioeconomic, health, environmental, climate, and heat illness. The municipalities engaged in the program in its first four years are Barre City, Bennington, Bradford, Brattleboro, Newport City, Rutland City, and St. Albans City.

Residents select up to two free trees and use the Arbor Day Foundation's software interface to identify the ideal tree planting locations on their property to maximize the air, water, energy, and carbon benefits of their tree(s). VT UCF coordinates community tree pick-up events and provides guidance on proper tree planting and care to the participants. The Arbor Day Foundation provides an impact report (see graphic below) to communicate quantified benefits of the program over time. VT UCF intends to continue to offer this program to targeted municipalities annually.

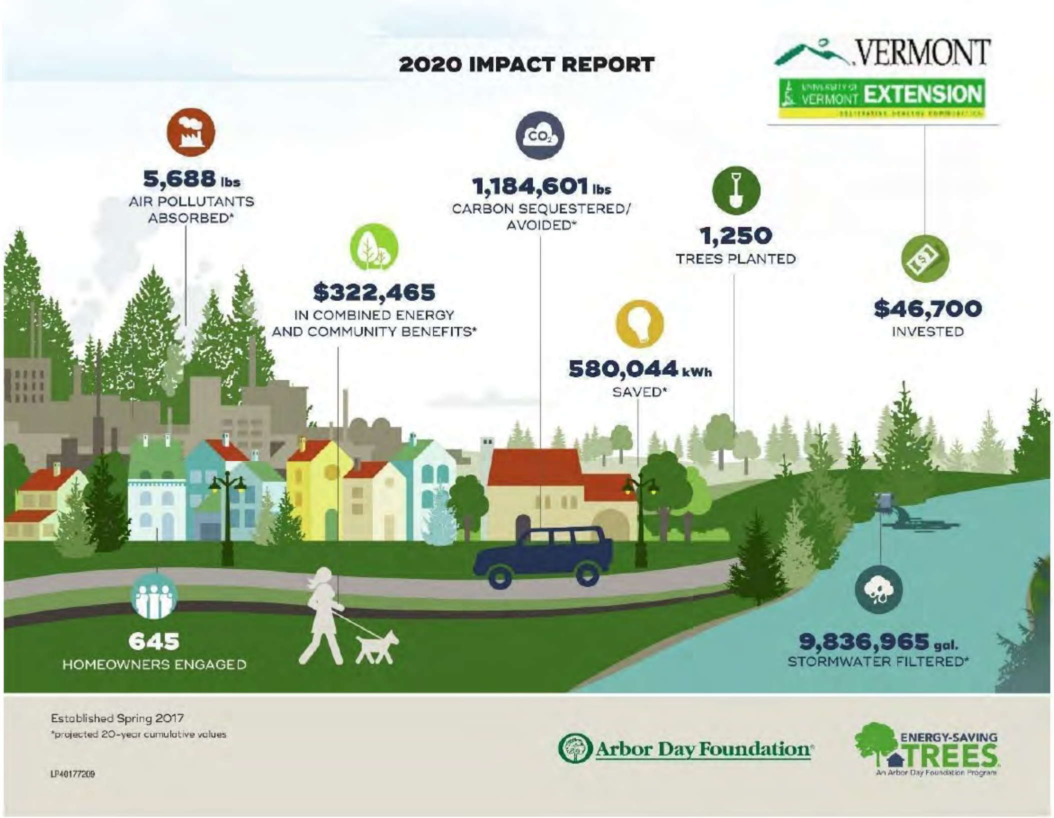


Figure 2-24: Impacts of the Vermont Urban and Community Forestry Program

1.21 TRACEABLE ACCOUNTS

Traceable accounts describe the categories of confidence level and the confidence level for each key message. These follow the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

Confidence level	**Very high**	**High**	**Medium**	**Low**
Description	Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus	Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message 1: Climate change is expected to shift growing conditions for forests in Vermont, becoming more favorable for southern-adapted tree species and less favorable for cold-adapted tree species. Species that will benefit from this change include northern red oak, shagbark hickory, and black cherry. Species including sugar maple, balsam fir, yellow birch, and black ash will be negatively impacted. While growing conditions will be significantly different by 2100, actual change in forest makeup will follow, as older trees die and are replaced by young ones.	
Confidence level	High
Major uncertainties	Modeling the future is inherently uncertain. While models agree on the general trend that Vermont's forests will become increasingly suitable for southern-adapted tree species, the particulars of how this shift will play out are uncertain.
Evidence base	References: Iverson et al., 2008, 2019; Nevins et al., 2021; Peters et al., 2020

Key message 2: Forest productivity, or the accrual of plant biomass, is expected to increase in Vermont in the short term, but productivity will be highly variable between species and will likely decrease overall. Factors impacting productivity positively include longer growing season length and CO_2 fertilization. Factors impacting productivity negatively include high summer temperatures, short-term drought, nutrient loss from soils, and atmospheric deposition. Productivity is an important indicator of forest health and carbon sequestration and storage.	
Confidence level	Medium
Major uncertainties	Modeling suggests that productivity will increase under climate change, but modeling is inherently uncertain. It is more likely that the factors decreasing productivity will increase with climate change and outweigh the benefits provided by the lengthened growing season and elevated CO_2 levels.
References	Campbell et al., 2009; Contosta et al., 2017; Duveneck et al., 2016; Norby et al., 2010; Ollinger et al., 2008; Pardo et al., 2011

Key message 3: Climate change is expected to continue worsening threats from invasive plants, insects, and diseases to the health of Vermont’s forests. These threats are compounded by other climate-related factors, such as worsening storms and increasingly irregular precipitation.	
Confidence level	High
Major uncertainties	Newly introduced forest pests or pathogens are likely, and their interactions with climate are unknown. Severity of biotic disturbances rely on multiple factors including temperature, precipitation, land use/human intervention, and the specific interactions with each species.
References	Dobson and Blossey, 2015; Lovett et al., 2016; McAvoy et al., 2017; Seidl et al., 2014; Slippers et al., 2011; Stephanson and Coe, 2017

Key message 4: Warmer winters and wetter summers brought on by climate change are already limiting active forest management by shortening the time frames that forest operations can take place on the ground. Ground conditions for forest management are projected to worsen, potentially leading to cascading negative effects on rural economies, forest product markets, and management for forest health and climate adaptation.	
Confidence level	High
Major uncertainties	Locally specific climate effects will be quite variable, so it is hard to project site-level forest management effects. Rural economies and forest products markets may show resiliency in their responses to diminished forest product availability.
References	Bick et al., 2019; Contosta et al., 2019

Key message 5: Land use change and parcelization, specifically conversion to residential or commercial use, are a major threat to forest health and productivity, release stored carbon, and potentially limit both ecosystem function and ability of forests to mitigate climate change through carbon uptake.	
Confidence level	Very high
Major uncertainties	Predicting future human migration patterns has inherent uncertainty. The science of carbon storage is continually evolving.
References	Fidel et al., 2018; Schultz et al., 2017; USDA Forest Service, 2020

Key message 6: Increasing forest adaptive capacity through forest management can help forests retain ecosystem function during a changing climate. Although forest adaptation is a new and evolving field, current methods to achieve increased adaptive capacity include increasing forest structural complexity and enhancing compositional and functional diversity and redundancy.	
Confidence level	High
Major uncertainties	Forest adaptive capacity and adaptive silviculture can increase forest resilience, but research outputs indicating specific impacts are limited, as this is a relatively new field.
References	Messier et al., 2019; Millar et al., 2007; Nagel et al., 2017

Key message 7: Climate change impacts will be more severe for urban trees. Urban trees are highly vulnerable to climate change because of the effects of the built environment on temperature and water cycling, and additional stressors associated with urbanized areas like soil compaction, soil fertility, and pollution.	
Confidence level	High
Major uncertainties	None
References	Fahey et al., 2013; Foran et al., 2015; Solecki and Marcotullio, 2013; Tubby and Webber, 2010

Key message 8: The importance of Vermont's urban trees under a changing climate will be increasingly important to humans because of the services they provide. Because of the high population density and lower tree cover in urbanized areas, per-tree ecosystem services can be higher than in a forest setting. In addition to critical climate and ecosystem benefits, urban trees mitigate the urban heat island effect through cooling and shading and reduce stormwater runoff along impervious surfaces from extreme rainfall events.	
Confidence level	High
Major uncertainties	None
References	Millward et al., 2014; Nowak et al., 2020, 2013; US EPA, 2014

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1.23 RESOURCES

- As a subset of the references listed below, the following resources are likely to be useful for readers interested in practical information and more detail about the topics discussed.
- Climate Change Tree Atlas (https://www.fs.fed.us/nrs/atlas/tree/ provides further information about predicted suitable habitat shifts and adaptability for individual tree species.
- VTInvasives.org (https://www.vtinvasives.org) contains a plethora of helpful guides to the invasive species affecting Vermont’s forests.
- Ten Recommendations for Managing Ash in the Face of Emerald Ash Borer and Climate Change (https://forestadaptation.org/sites/default/files/Ten-Recommendations-for-Managing-Ash.pdf) provides practical management recommendations for ash.
- Forest Carbon Markets for Vermont Landowners (https://fpr.vermont.gov/sites/fpr/files/Forest_and_Forestry/Climate_Change/Files/ForestCarbonOffsetsForVermontLandowners_Mar2021.pdf) is an in-depth resource detailing the process of a carbon offset project and specific recommendations for landowners to pursue.

- Climate Change Response Framework (https://forestadaptation.org/) describes resources on forest adaptation and access to the forest adaptation workbook.
- Adaptive Silviculture for Climate Change (https://www.adaptivesilviculture.org) provides operational examples of adaptive silviculture in action.
- Forest Impacts of Climate Change: Monitoring Indicators (https://www.uvm.edu/femc/climate_indicators/) includes climate-change indicators for Vermont, New York and greater New England across categories like aquatic systems, forest systems, trees and wildlife.

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2 WATER RESOURCES

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2.1 KEY MESSAGES

1. Due to extreme variation in precipitation with our changing climate, periods of prolonged dry-spells and drought, coupled with higher water usage in snowmaking and agriculture could exacerbate low water availability.
2. Increases in overall precipitation and extreme precipitation have caused streamflows to rise since 1960. Climate change will further this pattern, although the overall increase in streamflow comes with disruptions in seasonal flows cycles.
3. Increases in heavy precipitation jeopardize water quality in Vermont. Storms produce large runoff events that contribute to erosion and nutrient loading. Combined with warm temperatures, this creates favorable conditions for cyanobacteria blooms.
4. Increased occurrence of high streamflows increase the risk of flooding that causes damages to many roads and crossing structures. Risk reduction requires addressing outdated and unfit structures.
5. Nature-based solutions are an effective, low-cost approach to climate change adaptation. River corridor, floodplain, and wetland protection dampen flood impacts and improve water quality along with green infrastructure.

2.2 BACKGROUND

Key Point: Historical changes in total precipitation, heavy precipitation events, and temperature have had observable impacts on Vermont's water resources.

2.2.1 Increasing water

Precipitation in Vermont and the Northeast has been steadily increasing, although prolonged dry-spells and droughts are more common (see Climate Change in Vermont chapter). Recent evidence of climate change and its impacts give a sense of near-term (10-30 year) trends that are likely to continue. Increasing precipitation is expected to continue in Vermont and throughout the Northeast through the 21st century (Dupigny-Giroux et al., 2018; Guilbert et al., 2014). In Vermont, average annual precipitation has increased by 7.5 inches since the early 1900s, and has been increasing at a rate of 1.4 inches per decade in the same period (see Climate Change in Vermont chapter).

Increases in heavy precipitation events (greater than 1 inch of precipitation a day) are projected to continue throughout New England at a rate of 15% or more compared to the historical baseline (Dupigny-Giroux et al., 2018). Heavy precipitation events have increased in Vermont with decadal averages of 6.2 days/year in 1900s, 5.8 in 1960s, 8.4 in 1990s and 8.7 today (see Climate Change in Vermont chapter). Heavy precipitation results in higher volumes of stormwater runoff (LCBP, 2015), which can carry sediment and nutrients to our streams and lakes. For example, only 6% of the Lake Champlain Basin is impervious surfaces but these developed areas discharge more than other land uses (e.g., agriculture) (LCBP, 2018). Increased runoff drives erosion and moves contaminants that impair water quality to our lakes and rivers.

High-magnitude storm and/or precipitation events increase the likelihood of flooding (Guilbert et al., 2015). Flooding impacts range from property damage to infrastructure failure to loss of human life. How Vermont manages its natural resources, like its floodplains and wetlands, will play a large role in the future under altered conditions. Wetlands and riparian forests can attenuate water flows by holding water during times of extreme precipitation and releasing stored water during times of low flow. These land covers can both reduce flooding and effects of drought.

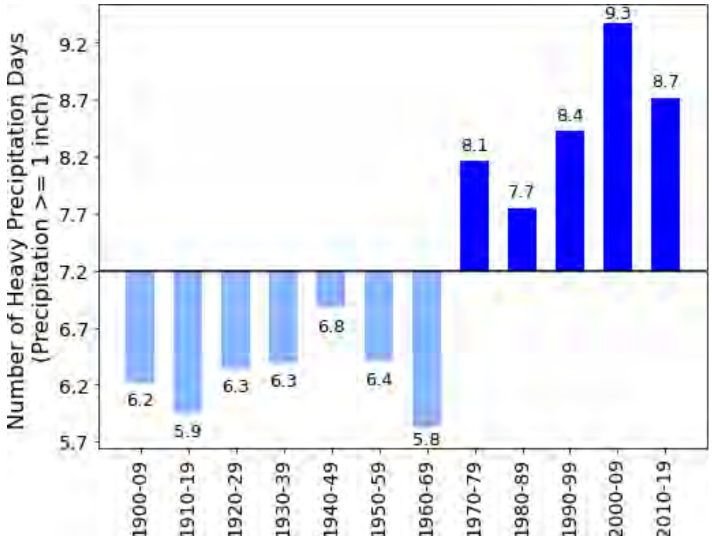


Figure 1-9 (see Climate Change in Vermont chapter). Decadal averages of the observed number of days per year with more than 1 inch of precipitation, computed for the state of Vermont based on available data for each decade. Decadal average values are plotted above and below the 1900–2019 mean value (solid black line).

2.2.2 Water shortages

At the other extreme, Vermont is beginning to experience more variability in precipitation such as prolonged dry spells and drought (see Climate Change in Vermont chapter). Droughts are projected to become more common in Vermont over the coming century (Betts, 2017). Unseasonable reductions in precipitation puts water supplies at risk in an era when water use is projected to increase for certain sectors. It is noteworthy that 60% of Vermonters use groundwater as their drinking water source (VT DEC, 2018). Natural infrastructure, such as wetlands, may be used to increase resilience as they attenuate flows to mitigate effects of drought.

2.2.3 Water temperatures

Air temperature increases have been observed in Vermont (see Climate Change in Vermont chapter), and are projected to increase by about 0.5°C per decade through the late 21st Century (Guilbert et al., 2014). Warming winter temperatures will result in less frozen precipitation and earlier spring thaw of snow and ice (Betts, 2017). Annual snowfall has declined by 10 inches relative to the 1960s, even as total precipitation increased; precipitation is falling as rain rather than snow due to warming conditions. Ice-out is also moving earlier by several days on Vermont's inland lakes (see Climate Change in Vermont chapter).

These temperature increases are reflected in the water temperatures of Vermont's lakes and rivers. According to measurements taken in ten regions of Lake Champlain, summer surface water temperatures have increased significantly in the last 50 years. An analysis of August lake temperature from 1964-2009 yielded an increase of 1.6 to 3.8°C (up to 0.085 °C/year). Summer air temperatures in the Lake Champlain Basin increased by about 0.037 °C/year from 1976-2005 (Smeltzer et al., 2012). Summer lake temperatures matched and even surpassed the rate of increase for air temperatures, illustrating the effect of warming climate. Researchers attributed these results to declining ice cover in Lake Champlain. With the absence of ice, the surface layers of the water begin to absorb radiation early in the spring, even as lower strata remain cooler (Smetzer et al., 2012). Warming temperatures further enforce thermal stratification because warmer water is less dense, so it remains on top, resisting mixing of the layers (US EPA, 2013).

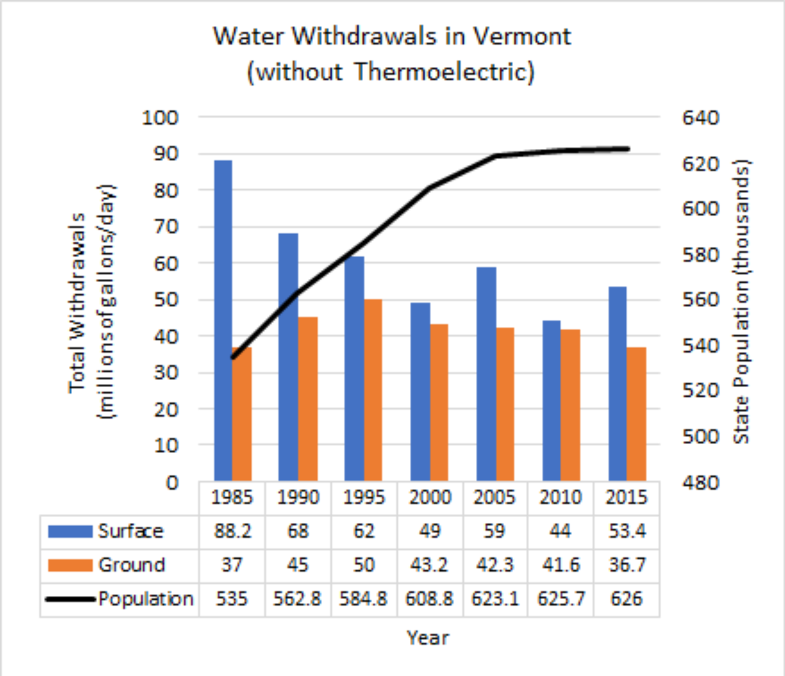
There is also evidence that temperatures in many rivers and streams have increased over time in the United States. Stream temperatures are subject to many factors, including groundwater inputs, geography, dams, and thermal discharge from plants, on top of air temperature and solar radiation (Kaushal et al., 2010). Water temperature does not fluctuate like air temperature, since cool groundwater inflows (e.g., wetland seeps) tend to stabilize river temperatures (Hodgkins & Dudley, 2011). However, despite differences in environmental conditions, many streams have shown increases consistent with long-term warming (Kaushal et al., 2010) This has especially negative impacts for aquatic biota, like cold-adapted fish species (Hodgkins & Dudley, 2011) (see Fish and Wildlife in Vermont chapter).

2.3 WATER SUPPLY AND USE

Key Point: Water supplies are already under stress in some areas of Vermont, and usage will likely increase for certain sectors. Increased occurrence of drought due to climate change will exacerbate this effect.

Water is sourced from surface water, such as lakes, rivers, and wetlands, and groundwater (water stored in the soils and bedrock). Precipitation runs off into surface waters, and it recharges groundwater that in turn supplies base flow to surface sources. About 60% of Vermonters rely on groundwater for drinking (VT DEC, 2018). Vermont's only thermoelectric power plant, Entergy Vermont Yankee, depended almost exclusively on surface water (VT DEC, 2018). Entergy Vermont Yankee withdrew over 340 million gallons of surface water every day in 2010. It was decommissioned in 2014 (VT DEC, 2018) (see Energy chapter).

Water use in Vermont has decreased steadily over time (Figure 3-1) and dramatically from 2010 to 2015 due to the Entergy Vermont Yankee power plant's closure (USGS, 2021). This is consistent with trends throughout the United States, where water withdrawals peaked in 1980 and have remained relatively steady with modest decreases, despite population growth, more widespread irrigation, and industrial usage. This demonstrates the power of efficient water systems and conservative usage behavior (USGS, n.d.).



	1985	1990	1995	2000	2005	2010	2015
🟦 Surface	88.2	68	62	49	59	44	53.4
🟧 Ground	37	45	50	43.2	42.3	41.6	36.7
— Population	535	562.8	584.8	608.8	623.1	625.7	626

Figure 3-1. Statewide water withdrawals in Vermont by source, surface water or groundwater, and population growth from 1985 to 2015. Surface water withdrawals used for thermoelectric power are not included. (VT DEC, 2018).

Freshwater resources undergo stress in certain areas and/or times (e.g., dry spells) in Vermont (USGS, 2021). For example, the town of Brattleboro utilizes a surface water reservoir that is often depleted during times of drought or high demand. The town relies on backup groundwater wells (Brattleboro Public Works Department, n.d.)

Surface water and groundwater sources are both vulnerable to changes in climate. During the summer months, there is an increased probability of drought and warmer temperatures drive higher evaporation levels. Combined with low precipitation, dry conditions result in reduced surface water and groundwater supplies (Betts, 2017). Communities like Brattleboro that rely on already-stressed water sources will be put in increasingly precarious positions. Conservative use and efficient water infrastructure have already proved effective and may be vital in the future (see Community Development chapter).

Warming temperatures also lead to decreased winter snowpack and earlier spring snowmelt (see Climate Change in Vermont chapter). Historically, groundwater levels peak in March or

April due to gradual recharge from snowmelt (Dudley & Hodgkins, 2013). With less snowpack and earlier snowmelt, groundwater may be more easily depleted moving into the summer months during dry conditions. Conversely, the increase in Vermont's heavy precipitation events (see Climate Change in Vermont chapter) do little to recharge groundwater stores. The vast majority of groundwater recharge comes from the small, frequent precipitation events, whereas high-intensity storms lend more to stormwater runoff into streams, rivers and lakes (LCBP, 2015).

2.3.1 Winter Recreation Water Use

As the climate changes, demand for water may increase in certain industries. Warming winter temperatures coincide with higher likelihood that winter precipitation will fall as rain instead of snow (Betts, 2017). For Vermont's busy winter sports industry, this threatens to shorten the season suitable for winter sports and reduce snowpack (see Recreation and Tourism chapter). Guilbert et al. (2014) estimated that annual snowfall will decrease roughly in half (47% to 52% by the late 21st Century) for several ski resorts in the Lake Champlain Basin.

In Vermont, natural snowfall is commonly supplemented with human-made snow which requires a reservoir of stored water; many winter resorts have artificial or natural water reservoirs for quick withdrawals, some drawing from multiple surface water sources (Figure 3-2) (Wilson et al., 2018). Snowmaking withdrawals consistently reach 30 million gallons per winter season (defined here as November through February of the next year) across ten of Vermont's major ski areas.

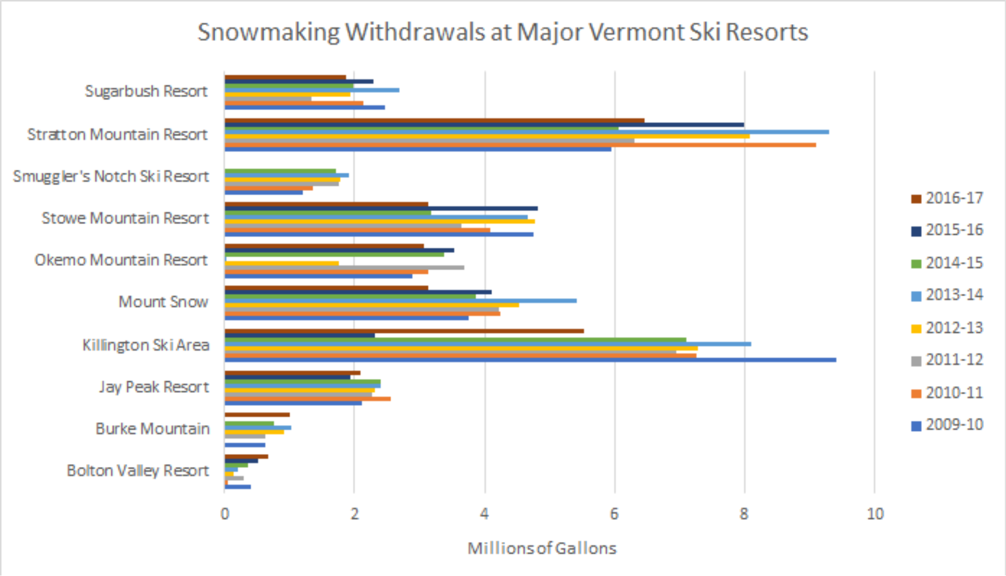


Figure 3-2. Water withdrawals (in millions of gallons) for snowmaking by ski area and winter season. This represents a sum of all withdrawals for that resort from November - February of the next year. Data was not available for every year at every site. All data is openly available at https://anrgeodata.vermont.gov/datasets/snowmaking-withdrawal

Winter temperatures are rising faster than any other season (see Climate Change in Vermont chapter), so natural snowfall and suitable conditions for supplemental snowmaking will both decrease by the end of the 21st Century (Guilbert et al., 2014). Snowmaking requirements are projected to increase significantly for many of Vermont's resorts, potentially by 25% by 2040 (Dawson & Scott, 2007). Water availability, in addition to temperature suitability, must be recognized in considering the viability of the winter sports industry in the Northeast under climate change (Wilson et al., 2018). February Median Flow (FMF) is a particularly important metric for water withdrawals from Vermont rivers, as the FMF value determines the minimum flow rate that must be maintained (at or above) when water is withdrawn for snowmaking per Vermont rules (VT ANR, 1996) (see Recreation and Tourism chapter).

2.3.2 Agricultural Water Use

Water usage is incredibly important in agriculture, especially as the climate changes. In Vermont, 85-90% of farms rely on groundwater sources for agricultural purposes (VT DEC, 2018). The amount of land in Vermont that uses irrigation has almost doubled since 1995, yet water usage for irrigation has remained relatively stable in those twenty years, which is consistent with long-term national trends (Figure 3-3) (USGS, n.d.).

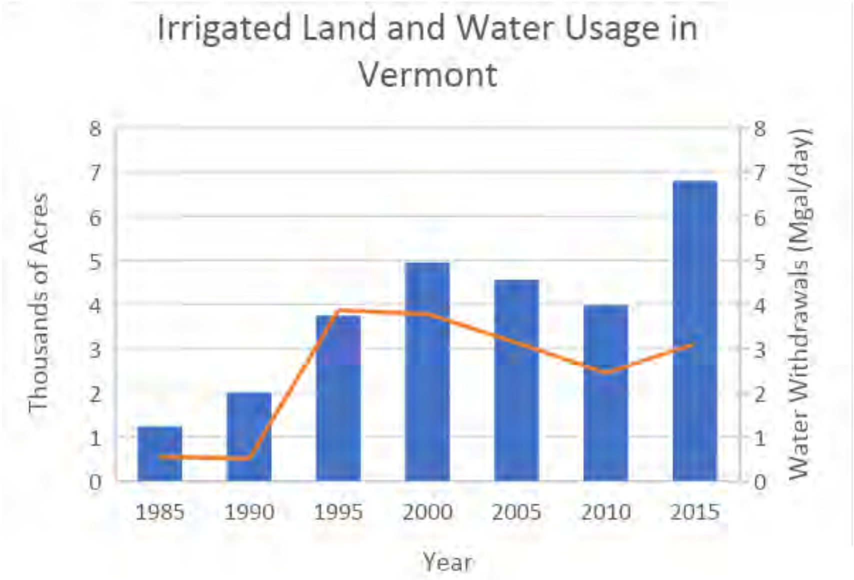


Figure 3-3. Irrigation in Vermont from 1985-2015, measured by the amount of land using irrigation (blue bar, thousands of acres) and water withdrawals for irrigation (orange line, millions of gallons per day). All data is openly available at https://waterdata.usgs.gov/vt/nwis/water_use/

Efficient irrigation systems have been key to maintaining crops without draining water supplies (Schaible & Aillery, 2017). However, these increases represent only a small proportion of the 1.3 million acres of land in agricultural use in 2016 in Vermont. Of the 535,100 acres that was cropland, irrigated lands amount to only about 1.3%, considering that about 6800 acres of land was irrigated in 2015 (Farmland Information Center, 2016).

Future changes in climate, including variability in precipitation, summer dry spells, and increased evapotranspiration, are expected to drive up implementation of irrigation systems in the Northeast and throughout the U.S. (Schaible & Aillery, 2017; Wolfe et al., 2018). Efficient water usage strategies will continue to be important in the future to cope with changing conditions (Schaible & Aillery, 2017) (see Agriculture and Food Systems chapter).

2.4 STREAMFLOW

Key Point: Average annual streamflow has increased in Vermont over time and across most seasons. Further increases can be expected under a wetter climate with intense storm events, creating challenges for water retention and flood risks.

Changes in precipitation and storm patterns are evident in Vermont's waterways the past few decades. Streamflow can be used as an indicator because the amount of precipitation directly affects how much water ends up in streams and rivers. Base flow of streams is derived long-term from groundwater storage, bank storage, and landscape sources like lakes, ponds, and wetlands that drain in. Storm flow adds on to the base flow when precipitation runs off into the stream in the short-term (Hodgkins & Dudley, 2011). Following a given precipitation event, runoff quantities depend on many factors, like land use, topography, vegetation, and soil properties. Urban areas with impervious surfaces and lands lacking vegetation allow more runoff than those that are forested (LCBP, 2015), although given the small total area in impervious surfaces the changes in runoff are largely attributable to increased precipitation.

Beyond an indicator of climate change, streamflow is a measure of water availability and flow power. For example, snowmaking guidelines in Vermont keep a discharge threshold to determine water supply for withdrawals (VT ANR, 1996) (see Recreation and Tourism chapter). Similarly, the U.S. Fish and Wildlife Service uses streamflow as an indicator of critical habitat for native fish (Lang, 1999). Flooding events can also be directly monitored by assessing discharge levels, and drought periods are likewise characterized by low flows (see Climate Change in Vermont chapter). Therefore, streamflow is a direct measure of how much water is running through a waterway, which has practical, ecological, and economic ties.

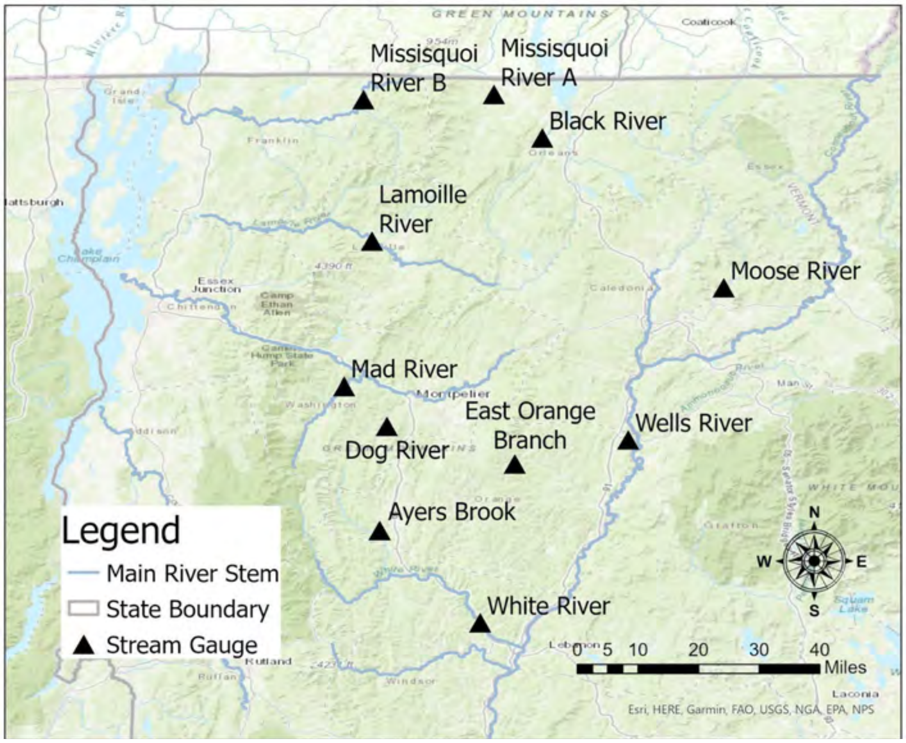


Figure 3-4. Map of 11 streamflow gauge sites in Vermont used in analysis.

124 USGS gauges are installed in streams and rivers throughout Vermont to measure discharge, the amount of water that passes by the point of the gauge in a certain time interval in cubic feet per second (CFS). Of these, a subset of six belong to the Hydro-Climatic Data Network, chosen by the USGS for climatic study due to limited outside influence, such as impoundments or diversion. The other five stations included in this analysis are approved in other literature as having minimum external influences (Hodgkins, 2010) (Figure 3-4). Therefore, the trends observed at these stations can be attributed to changes in climate.

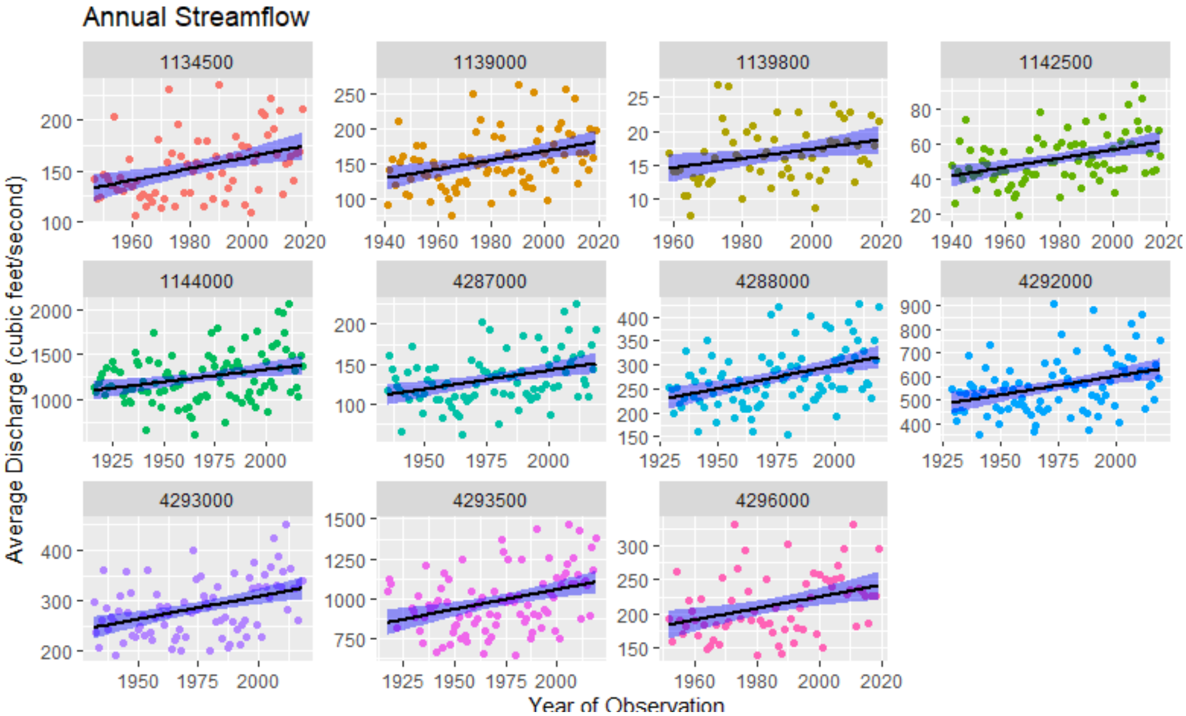


Figure 3-5. Average annual streamflow since 1960 at 11 stream gauges in Vermont. Linear trendlines (black) with 95% confidence intervals (blue). Data from https://waterdata.usgs.gov/vt/nwis/sw

All 11 streamflow gauges showed statistically significant (p<0.05, Mann's Kendall) increases in average annual streamflow since 1960 (Table 3-1) and for their full period of record. For 9 out of 11 sites, the trend was very significant (p<0.01, Mann's Kendall). This is consistent with increased annual precipitation and runoff due to climate change (see Climate Change in Vermont chapter). This trend is likely to continue with increased total precipitation and more frequent storm events (Guilbert et al., 2015).

Table 3-1. Sites used in streamflow analysis and p-values obtained from Mann-Kendall test of time series by site.

USGS Site ID	**Site Name**	**Mann Kendall, p-value (since 1960)**				
		Annual	Winter	Spring	Summer	Autumn
01134500	MOOSE RIVER AT VICTORY	0.0009	9.55E-05	0.7258	0.0206	0.0228
01139000	WELLS RIVER AT WELLS RIVER	0.0015	0.0015	0.9851	0.0006	0.0162
01139800	EAST ORANGE BRANCH AT EAST ORANGE	0.0216	5.91E-05	0.1913	0.0040	0.0067
01142500	AYERS BROOK AT RANDOLPH	0.0005	0.0001	0.6192	0.0004	0.0120
01144000	WHITE RIVER AT WEST HARTFORD	0.0023	8.76E-05	0.7162	0.0004	0.0419
04287000	DOG RIVER AT NORTHFIELD FALLS	0.0009	0.0002	0.7450	0.0005	0.0287
04288000	MAD RIVER NEAR MORETOWN	0.0015	0.0001	0.2322	0.0006	0.1243
04292000	LAMOILLE RIVER AT JOHNSON	0.0041	0.0006	0.9847	0.0326	0.0794
04293000	MISSISQUOI RIVER NEAR NORTH TROY	0.0005	7.75E-06	0.6361	0.0174	0.1152
04293500	MISSISQUOI RIVER NEAR EAST BERKSHIRE	0.0003	3.81E-06	0.9036	0.0296	0.0817
04296000	BLACK RIVER AT COVENTRY	0.0058	9.89E-06	0.7741	0.0502	0.0406

Discharge was also analyzed by meteorological season to see at what times of year these trends are most evident. Streamflow levels naturally vary between seasons. Absolute flow values are highest in the spring due to melting snowpack and precipitation running off of saturated or frozen soils. Following leaf-out of deciduous vegetation, evapotranspiration picks back up, producing lower base flows in the summer, though storms in the summer and autumn add on. Winter precipitation falling as snow accumulates before returning to the watersheds in the spring as snowmelt (Hodgkins & Dudley, 2011) (see Climate Change in Vermont chapter). This seasonal cycle is important for water availability, such as for snowmaking, and ecological function, such as migrating fish species (Dudley et al., 2017).

Monthly data was divided into four seasonal intervals: December to February for winter, March to May for spring, June to August for summer, and September to November for autumn. A significant positive trend ($p<0.05$) was observed for all sites in winter and summer, and for 10 out of 11 sites in autumn. These trends are consistent with observed increases in annual and heavy precipitation during these seasons (see Climate Change in Vermont chapter).

Spring is the only season in which significant changes in streamflow were not observed, with trends remaining relatively steady ($p>0.05$, Mann's Kendall). This is surprising because spring precipitation has increased over time like the other seasons (see Climate Change in Vermont chapter). One explanation for this is based on temperature changes, not precipitation. Temperatures are warming most significantly during winter, with total snowfall trending downwards since the 1960-70s, but precipitation trending upwards. Therefore, winter precipitation is falling more often as rain rather than snow, leading to less snow accumulation (see Climate Change in Vermont chapter). This snowpack is also melting earlier in the year. Dudley et al. (2017) analyzed historical trends in snowmelt-related streamflow timing using the winter-spring center of volume date, or the date when half of the volume of water for the winter and spring seasons has passed the gauge. They found that in the Eastern United States, the average for this date has advanced by over 8 days between 1940 and 2014, driven by February-May temperature increases. Therefore, water that is typically stored as snowpack, which later melts contributing to spring streamflow, is now falling as rain in the wintertime. The snowpack that does form is melting earlier in the winter-spring season, potentially contributing to the steady trend exhibited by spring streamflow over time.

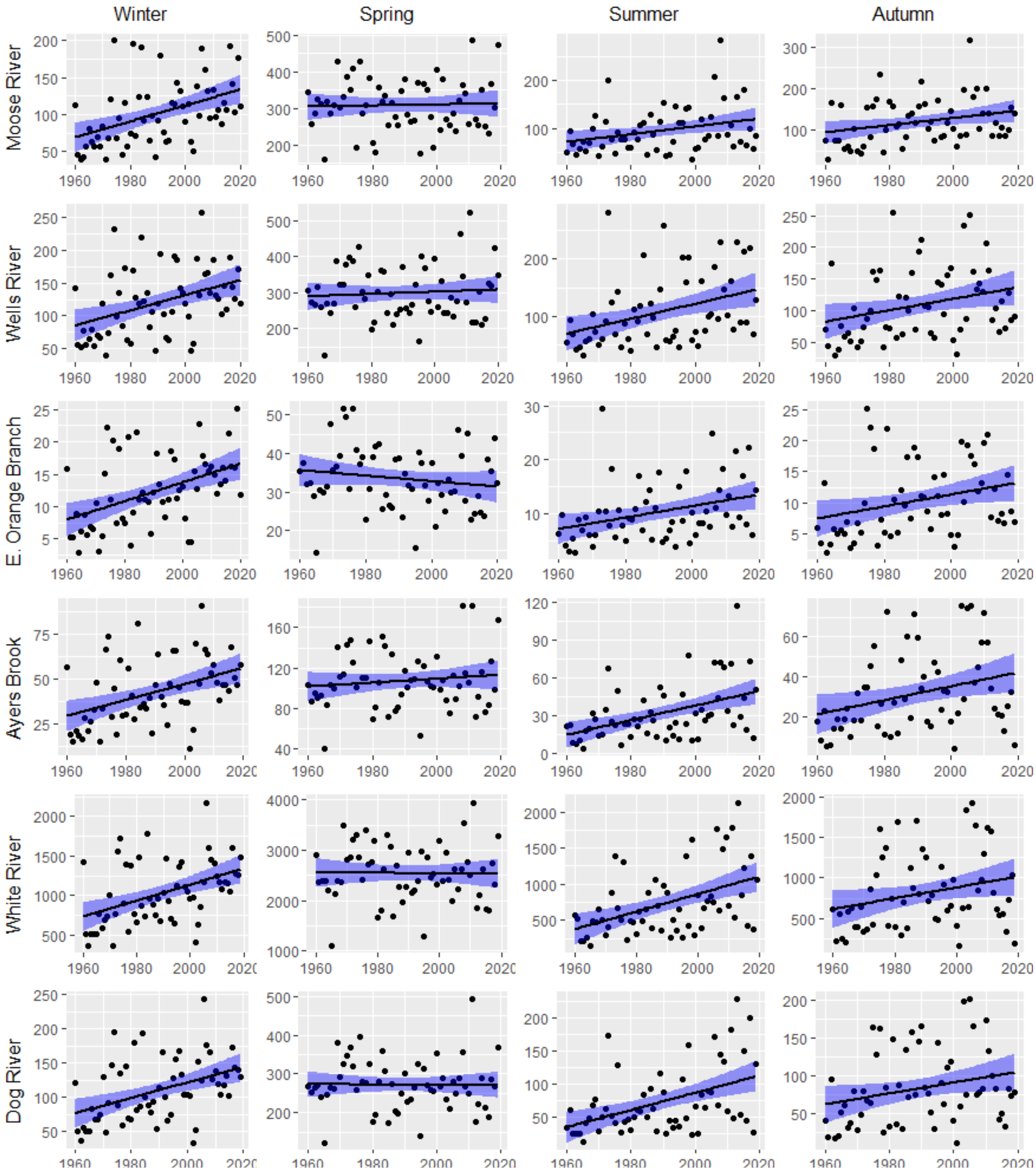


Figure 3-6a. Average seasonal streamflow since 1960 at 6 stream gauges in Vermont. All data is openly available at https://waterdata.usgs.gov/vt/nwis/sw

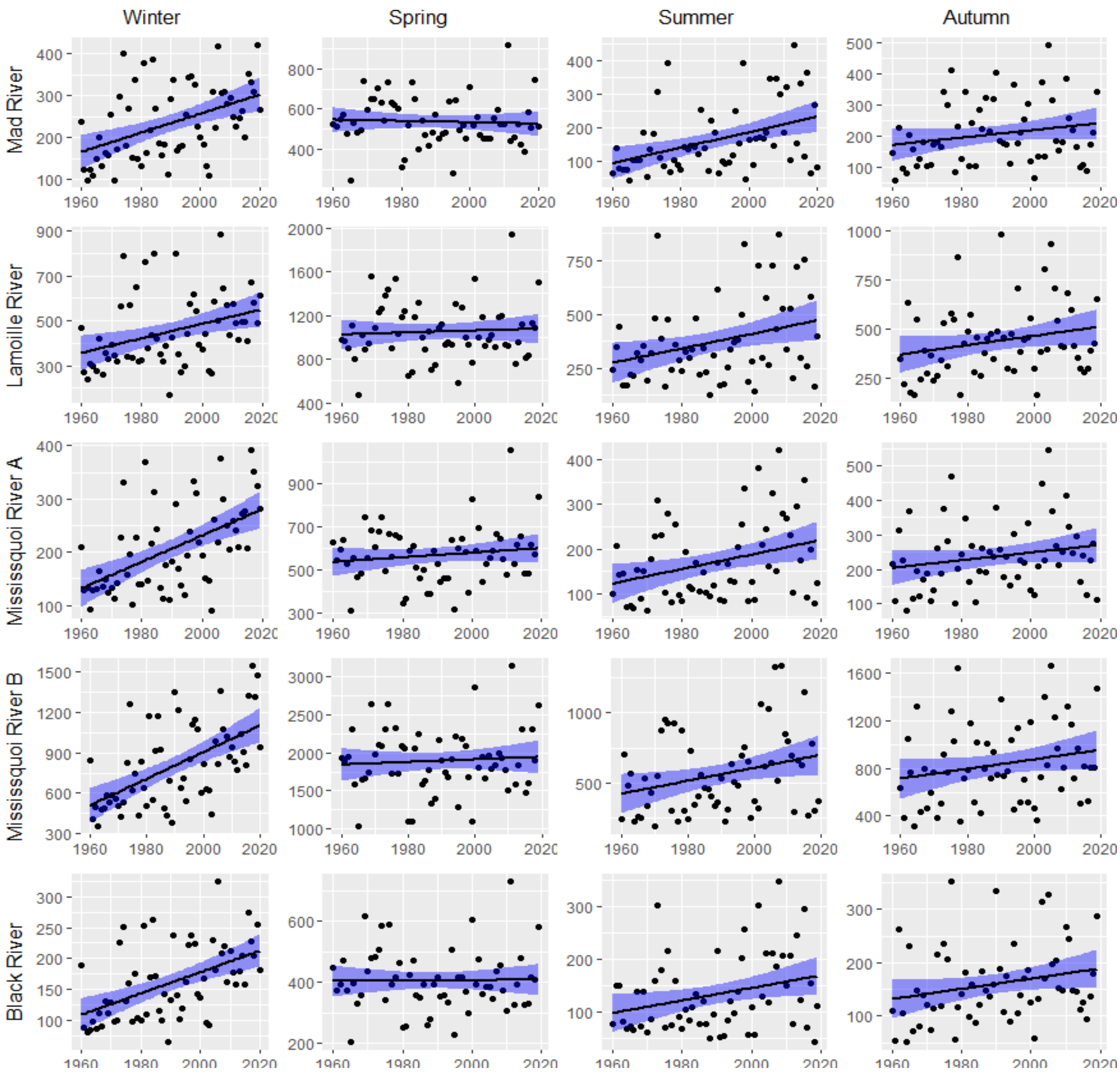


Figure 3-6b. Average seasonal streamflow since 1960 at 5 stream gauges in Vermont. All data is openly available at https://waterdata.usgs.gov/vt/nwis/sw

2.5 WATER QUALITY

2.5.1 Nutrient and Sediment Loading

Key Point: Storms produce large runoff events that contribute to erosion and nutrient loading, which jeopardizes water quality.

Greater amounts of runoff not only leads to higher streamflows; it also drives erosion and carries pollutants and sediments into Vermont's waterways. In 2018, nutrients were the cause of impairment for 54.8 miles of Vermont's streams and rivers, and sedimentation impaired 63.1 miles (VT ANR & VT DEC, 2018). Lake Champlain Basin (including NY and VT), for example, has a ratio of 18:1 land to water; that is a primary reason water quality challenges result from land-based nutrient and sediment inputs. Vermont's lakes and ponds, as well as wetlands, can be hardened by sedimentation and excess nutrients. For example, buildup of sediments can alter hydrology, or invasive plants are able to colonize disturbed wetlands. Storms in particular contribute large volumes of nutrients and sediments in short amounts of time (Stockwell et al., 2020), and a reduction in the frozen period for soils may make them more susceptible to erosion. Segments of seventeen waterbodies (rivers or lakes) in Vermont are impaired due to stormwater runoff, while twenty-five are impaired by nutrients or nutrients and sediment and fifteen by sediment inputs (VT DEC, 2018). Therefore, as the climate changes and heavy precipitation events increase, these individual storm events play an oversized role in water quality impairment.

In Vermont, phosphorus is often considered the most troublesome pollutant. Phosphorus pollution comes from point sources like wastewater treatment centers, as well as non-point sources such as stormwater runoff and agricultural runoff. Phosphorus levels are over the allowed limit in many waterbodies, mostly from non-point sources. Reducing inputs from runoff, while far more difficult than for point sources, is imperative (Smeltzer et al., 2012). In 2016, the US Environmental Protection Agency (EPA) found that the leading contributor of phosphorus inputs into Lake Champlain is the agricultural sector, primarily from cropland and soil erosion (US EPA, 2016). Phosphorus accumulation in agricultural soils is a legacy of Vermont's agricultural identity, which cannot be avoided even with sharp reductions in current imports. Phosphorus continues to accrue by 5 kg per hectare per year in Vermont due to applications of manure and fertilizer, as part of the net importation of phosphorus in animal feed and fertilizer (Wironen et al., 2018) yet developed lands contribute twice the phosphorous load as agricultural lands (0.51 metric tons per square mile and 0.25 metric tons per square mile, respectively) (LCBP, 2018).

When soils erode, the sediments are released along with the nutrients they were trapping. Erosion on backroads, poorly managed ditches, and forestry practices are other significant contributors of phosphorus, but less so than agriculture (LCBP et al., n.d.; US EPA, 2016). Streambank erosion also contributes nutrients and high sediment volumes from unstable streams. Channels that have become artificially straightened become more powerfully erosive of stream banks causing incision (Kline & Cahoon, 2010). Approximately 75% of assessed river reaches in Vermont have become disconnected from their floodplains and thus are more prone to erosion (Henzel, 2016; Kline, 2016; Kline & Cahoon, 2010).

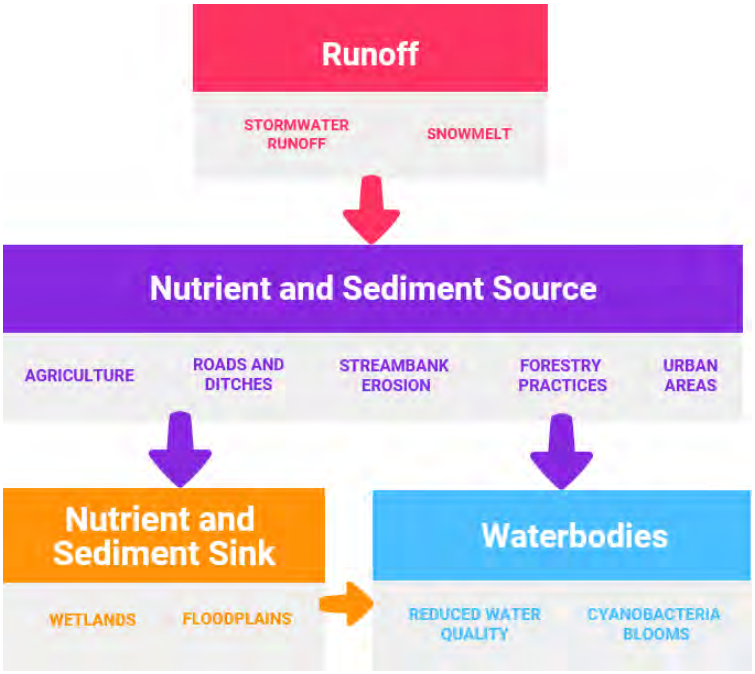


Figure 3-7. Flow chart showing relationship between runoff, nutrient and sediment loading, and water quality. This is not inclusive of all sources, sinks, and impacts, but is meant to aid in understanding elements included in the text. Flowpaths that include nutrient and sediment sinks in wetlands and floodplains will result in improved water quality compared to flow paths directly from nutrient and sediment sources to waterbodies.

As more high-intensity storms occur in Vermont, large runoff events will significantly impair water quality without substantial action to use nature-based solutions to minimize stormwater runoff (see Community Development chapter). A study examined sediment released by Tropical Storm Irene in the Mad River, Vermont watershed. Soil samples and aerial imagery pre- and post-

Tropical Storm Irene were used to calculate how much sediment and phosphorus were released due to erosion from high flows. The results suggest that this one extreme event delivered as much sediment and phosphorus into the stream as is normally exported over an entire year (Ross et al., 2019).

Adaptation measures, particularly in developed areas and farmlands, can help mitigate runoff volume and velocity. Payment for Ecosystem Services programs are an option for reducing phosphorus loading (see Agriculture and Food Systems chapter). Wetlands and floodplains are vital natural features that preserve water quality, and restoration is a cost-effective mitigation measure, such as in marginal farmlands (Rousseau, 2020). Implementation of green stormwater infrastructure can greatly reduce runoff to preserve water quality (LCBP, 2015) (see Community Development chapter).

Box 3.1 The Value of Water Quality in Lake Champlain

Though water seems a plentiful resource in Vermont, clean water is vital to its citizens' lifestyles and livelihoods. Lake Champlain alone is an economic powerhouse in terms of property value, tourism revenue, and employment opportunities. A 2015 study found that for the four counties in Vermont adjacent to Lake Champlain, just a one-meter decrease in water clarity has consequences. A one-meter decrease means that the water is less clear at shallower depths due to sediments and algae growth; this is measured by lowering an object into the water and recording the depth when it disappears. An extrapolated model shows that this loss in water quality would in turn lead to a loss of approximately 195 full-time jobs, a $12.6 million reduction in tourism expenditures, and a total economic reduction of nearly $16.8 million (Voigt et al., 2015).

2.5.2 Floodplains and River Corridors

The floodplain is an area outside a waterbody where floodwaters can go. When rivers are well connected to their floodplains, these riverside areas can accommodate the overbank flow, capture sediment, and store floodwaters to reduce the volume and peaks of flows experienced in downstream reaches. Floodplains host moist deep and varied soils and unique natural communities, and these stone-free floodplain soils are valued for agriculture and forestry. Sediments and nutrients carried in the water settle out onto the floodplain instead of routing back to the waterbody; maintaining water quality is an important ecosystem service provided by floodplains (Figure 3-7).

Stream and river channels adjust dynamically to accommodate the flow of water, sediment, and debris. River Corridors identify the minimum lateral area needed for stream and river channels to freely adjust and manage these forces. River Corridors in Vermont are mapped to include the channel meander belt and room for a stable vegetated bank (Kline & Cahoon, 2010). This vegetation helps to prevent streambank erosion (Singh et al., 2018).

River corridors and floodplains provide foundational ecosystem services with critical public safety, fiduciary, water quality, habitat, social and economic benefits. However, in the Northern hemisphere, over 95% of streams have been modified by human activity (Singh et al., 2018). Historical land use choices have involved channel and floodplain manipulation to straighten, dredge, armor, and berm rivers to protect riverside infrastructure. A straightened channel becomes more erosive and can lose functional connection with its floodplain. Within Vermont, over 75% of assessed streams have lost some degree of connection to the floodplain and are incised (Henzel, 2016).

2.5.3 Wetlands and Water Quality

Wetlands are inundated by surface water or groundwater seasonally, such as vernal pools, or year-round. They serve a variety of functions and values to human society, in addition to supporting robust plant and wildlife communities (see Fish and Wildlife in Vermont chapter) (VT DEC, 2019).

The impacts of climate change on wetlands are poorly understood, especially for freshwater inland wetlands like those in Vermont. Wetlands in Vermont do not face the same threats as coastal wetlands from saltwater intrusion, or wetlands in areas prone to frequent drought and wildfire. However, regardless of geographic region, wetland functionality can be impaired by increased temperatures, drought and flooding events, and carbon dioxide increases (Junk et al., 2013; Moomaw et al., 2018). Ephemeral wetlands, or vernal pools, depend largely on the length of time they are inundated, or the hydroperiod. Drought and flooding events can shorten or prolong the hydroperiod, making it less suitable for some wildlife that depend on them for habitat or breeding (Brooks, 2009) (see Fish and Wildlife in Vermont chapter). Wetlands' vulnerability to changes in climate goes in hand with the natural mitigation services they offer.

Wetlands play an important role in moderating the effects of climate change in terms of water quality. (Adusumilli, 2015; Junk et al., 2013; VT DEC, n.d.). Wetlands serve as natural filtration systems for nutrients and sediments (Carr et al., n.d.; VT DEC, 2019). The binding roots of wetland plants can remove up to 90% of sediments present in runoff or streamflow (VT DEC, n.d.). Excess nitrogen and phosphorus are taken up by wetland plants and recycled through the system (Junk et al., 2013; VT DEC, 2019). Because of these benefits, wetlands are regarded as a natural solution to impaired water quality and eutrophication (Lester et al., 2019; VT DEC, 2019).

A study in the Lake Champlain Basin was dedicated to optimizing wetland restoration to reduce phosphorus export (Lester et al., 2019). The researchers developed a framework based on ecosystem service modeling; how much phosphorus could be reduced for the lowest cost? They found that phosphorus exports throughout the basin could be reduced by 2.6% for a $50 million budget, and by 5.1% for a $200 million budget. With access to finer spatial resolution data, in order to locate "hotspots", phosphorus reduction could potentially reach twice that for the same budget. This study highlights the major role Vermont's wetlands take in clean water.

Another important way that wetlands increase resilience to climate change is through carbon sequestration. Carbon dioxide in the atmosphere is absorbed by wetlands, stored in plant biomass for decades and in its soils for potentially thousands of years (Carr et al., n.d.;

Milligan et al., 2019). The exact amount of carbon stored is difficult to determine, and it varies by location, wetland size, and other factors. Wetlands in the Northeast and Midwest store more carbon than any other region in the United States; one study estimated about 475 metric tonnes per hectare in the soils alone (Nahlik & Fennessy, 2016). Another calculated that wetland plants sequester over 8 tonnes of carbon per hectare every year, though for a specific wetland in Connecticut (Milligan et al., 2019). Wetlands also release carbon dioxide, through respiration, and emit methane, but they are largely considered valuable carbon sinks rather than sources.

Management decisions are key to maintaining wetlands as carbon sinks. In Vermont, over 35% of wetlands have been lost, mainly due to agricultural development (Dahl, 1990). Wetland drainage and alteration exposes the soils, liberating and releasing carbon into the atmosphere, turning a major carbon storage tank into a source instead. Newly created freshwater wetlands can take decades to centuries to become a carbon sink due to methane emissions, as roots and microbes accumulate (Moomaw et al., 2018). Wetland degradation has other far-reaching consequences, such as habitat loss for plants and wildlife, and functions for water supply, water quality, and flood control are also impaired.

2.5.4 Algae and Cyanobacteria Blooms

Key Point: Climate change creates favorable conditions for cyanobacteria blooms, which impact recreation, public health, and wildlife.

Nutrients feed algae growth in water bodies, which reduces water clarity and oxygen levels. Heavy precipitation produces large runoff events that carry these nutrients, particularly phosphorus, into Vermont’s waterways. Combined with warming temperatures, climate change could support the warm, nutrient-enriched environment that algae thrive in at the expense of fish and wildlife (LCBP, 2015).

Some algae are very dangerous to consume or come into contact with (see Human Health chapter). Cyanobacteria, or blue-green algae, are common lake organisms, but some produce cyanotoxins. Cyanobacteria blooms, or harmful algal blooms, are dense accumulations of blue-green algae. They have been observed in Lake Champlain since the 1970s, but were not consistently monitored until recently (Figure 3-8) (Shambaugh, 2020). They have dangerous health effects on humans and wildlife, and lead to disruptions in recreational activities when active blooms occur. In 2020, there were a record 44 beach closure days due to cyanobacteria blooms, compared to 9 in 2015 (VPR, 2020).

Climate change is expected to favor cyanobacteria growth, even over other types of algae. Recent research suggests that warming water temperatures lend cyanobacteria a competitive advantage, since certain harmful algae can grow better than non-harmful algae at relatively high temperatures (US EPA, 2013). Additional complexities include increasing chloride levels in lakes (Dugan et al., 2017; Smeltzer et al., 2012) that can play a role in cyanobacteria as well (Paerl & Huisman, 2008); chloride inputs come from applications of salt or brine to minimize ice on roads, which could be increasingly needed to manage conditions as winter precipitation transitions from snow to rain/ice (see Climate Change in Vermont chapter).

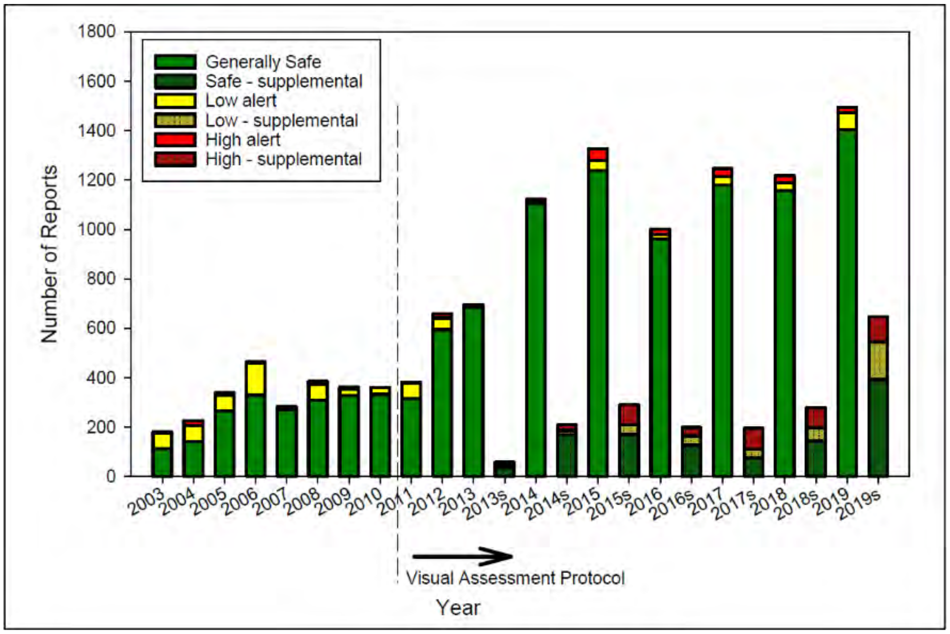


Figure 3-8. Cyanobacteria Monitoring in Lake Champlain since 2003 (Shambaugh, 2020). Cyanobacteria monitoring efforts have increased dramatically in recent years, composed of routine monitoring, visual assessments by volunteers, and supplemental reports. The visual assessment protocol was put in place for the 2011 monitoring season (dashed line). Green = Generally Safe, Yellow = Low Alert, Red = High Alert

Cyanobacteria blooms are likely becoming more common in Vermont (Figure 3-8). Northeastern sections of Lake Champlain have seen increases in cyanobacteria prevalence since the 1970s because they are phosphorus-impaired. For many of these segments, like Missisquoi Bay and St. Albans Bay (Figure 3-9), cyanobacteria have outcompeted other phytoplankton (Smeltzer et al., 2012). Certainly, Vermont's 2019 cyanobacteria monitoring program produced a higher number of total reports and alert reports than previous years (Shambaugh, 2020). All reports confirm the presence of cyanobacteria, but alert reports indicate larger amounts of cyanobacteria that could pose safety threats. Detailed tracking of dissolved oxygen, temperature, and blue green algae phycocyanin in St. Albans and Missisquoi Bays are available from a University of Vermont EPSCOR program.

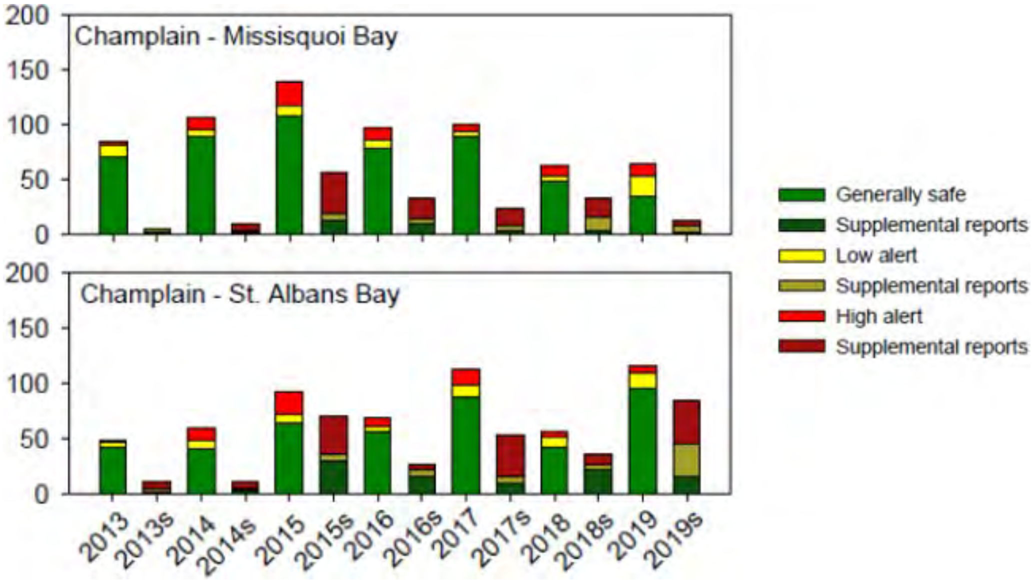


Figure 3-9. Cyanobacteria Monitoring Reports in Segments of Lake Champlain since 2013 (Shambaugh, 2020). Green = Generally Safe, Yellow = Low Alert, Red = High Alert. Shaded areas represent supplemental reports.

As the climate changes, warming lake temperatures and increased runoff can create favorable conditions for cyanobacteria to bloom (Smeltzer et al., 2012). Increases in bloom occurrence and severity can be expected while these trends continue to create a suitable environment.

2.6 FLOODING

Key Point: Damage from high flows is the single most costly type of disaster in Vermont, primarily due to the erosive power of water. Many roads and culverts are in conflict with the room needed by streams and rivers. River corridor and floodplain protection is critical to maintain floodplain function.

The most common recurring hazard event in Vermont is flooding. Damage is usually associated with the rise of river or lake levels and fluvial erosion, in which streambed and streambank erosion result in physical changes to the width and depth of the channel. Flash flooding can occur in small areas when a large amount of precipitation falls in a short period of time, often due to rapid rise of river levels with runoff from entrained thunderstorms. Over 75% of monetary flooding damages are due to fluvial erosion in Vermont (VT Emergency Management, 2018). Roads, crossings, homes, and businesses have been damaged and lives have been lost (State of Vermont, 2021).

Vermont has already seen increases in precipitation and streamflow that produce flooding conditions. Now a decade since the 2011 flooding events, it is important to not forget the insight gained. First, in the spring of 2011, high temperatures and rain brought on rapid melting of a deeper-than-average snowpack leading to widespread flooding in Lake Champlain tributaries in western Vermont and in the eastern Adirondacks. Though flood was not necessarily severe in any one tributary (with exceptions), it was the widespread nature of flooding in so many of the Lake Champlain tributaries that caused Lake Champlain to rise rapidly and to a high stage-- a record-breaking 103 ft above sea level, remaining above flooding level (100 ft above sea level) for two months (Betts, 2017; International Lake Champlain-Richelieu River Study Board, 2019; LCBP, 2013). A summary of this flooding event and suggestions for flood preparation are provided by the International Lake Champlain-Richelieu River Study Board (International Lake Champlain-Richelieu River Study Board, 2020).

This major flooding event was subsequently overshadowed by what followed in August: Tropical Storm Irene. High spring-summer precipitation and streamflow levels, combined with soils that were already very wet, allowed for severe flooding and damage across central and southern Vermont (Betts, 2017). Tropical Storm Irene led to over $1 billion in flood-related losses, 1500 displaced families, and 3500 residences damaged (Gourevitch et al., 2020). Flooding exceeded the 1% annual occurrence threshold, or a 1% probability that a flood of that magnitude would occur in a given year, in most areas affected and even the 0.2% value in some areas (Anderson et al., 2017).

The flooding events of 2011 will occur again, like the Great Vermont Flood of 1927 or the 1938 New England hurricane. There has already been an observed increase in watershed discharges (LCBP, 2015; Schiff et al., 2015) and, by design, the best contemporary Flood Insurance Rate Maps do not characterize likely future flooding conditions. Under likely climate conditions, augmented precipitation and runoff are anticipated (Guilbert et al., 2014). Rapid snowmelt in the spring, if there is substantial snowpack, can increase flooding conditions. As snow loading diminishes, frozen soil conditions will affect traditional spring flooding patterns including rapid river ice-melt. As high-magnitude storms are expected to occur more frequently, there is higher risk of costly, recurring flooding (Guilbert et al., 2015). The flooding events of 2011 may serve as a warning for what is to come and emphasize the need for action.

2.6.1 Floodplains and River Corridors

Key Point: Restoring and maintaining functional floodplains and river corridors are important in terms of climate-change induced flooding vulnerability and water quality.

Floodplain integrity is extremely important to flood mitigation in Vermont (Box 3.2). Currently only a third of communities in Vermont protect River Corridors and/or floodplains from adverse impacts, and very few have established protections for woody riparian buffers along banks (State of Vermont, 2021). Forested watersheds offer multiple benefits in terms of flooding mitigation by intercepting rainfall and detaining snowmelt. Forests promote gradual groundwater infiltration and return water to the atmosphere, whereas deforested landscapes allow fast runoff that leads to earlier storm peaks and damaging flows (see Climate Change in Forests chapter) (State of Vermont, 2021). In developing areas, where impervious surface is increasing, most communities in Vermont do not account for increases in offsite storm discharge in their development standards. Flood damage avoidance in Vermont requires more widespread adoption of "no adverse impact" standards to support the natural and beneficial functions of river corridors and floodplains.

As the climate changes and heavy precipitation increases, along with extreme events like Tropical Storm Irene, river corridor and floodplain protections are the least costly opportunity to avoid the loss of existing floodplain functions and heightened damages. In some locations, opportunities for disaster risk reduction may combine both the removal of buildings at risk as well as the re-connection of floodplains to restore ecological services. Many floodplain restoration operations employ functional floodplain connectivity measures and revegetation. Reconnecting floodplains will lead to improved accessibility between the stream and floodplain, such that sediments, and nutrients can be deposited. Revegetation aims to increase bank stability, reducing erosion, and it allows less runoff of sediments and nutrients into the stream (Singh et al., 2018). The assessment and prioritization of these restoration investments should consider both the protection of existing floodplain functions as well as the likely long-term value.

2.6.2 Wetlands and Flood Resilience

Key Point: Wetland conservation and restoration result in many ecosystem services and increase flood resilience.

Wetlands are critical points of flow reduction; they temporarily store stormwater and floodwater, then release them gradually, dampening high discharge. Wetlands decrease flood peaks by as much as 80% (VT DEC, n.d.). As aforementioned, over 35% of wetlands in Vermont have been lost, mainly due to agricultural development (Dahl, 1990). Complete removal of wetlands can result in a 200% increase in peak flows (Watson et al., 2016).

Therefore, wetland mitigation and restoration has become increasingly prioritized in federal and state policies. For example, in Vermont, for the period 2010-2012, 48.2 wetland acres were impacted or destroyed, requiring 323.2 acres mitigated for permits under the US Clean Water Act (Adusumilli, 2015). Restored ecosystem services were valued at about $140,000 per acre mitigated per year in the state of Vermont, totaling almost $2.75 million throughout the United

States (Adusumilli, 2015). This calculation takes into account restored water functions - supply, quality, and flood control - as well as recreational and commercial value, but excludes carbon sequestration.

However, created and restored wetlands may not be functionally equivalent to natural wetlands (Junk et al., 2013). After all, one acre of wetland loss in Vermont requires mitigation for almost six times the area (Adusumilli, 2015), incentivizing preservation over restoration. This is especially important for carbon sequestration. The protection of peatlands is the most relevant for carbon sequestration in Vermont. It can take thousands of years to accumulate the organic matter again. It is necessary to maintain original wetlands, while pursuing restoration and enhancement for areas that have been lost and degraded, especially for areas that provide the most services.

Box 3.2 Quantifying Flood Mitigation Services: The economic value of Otter Creek wetlands and floodplains to Middlebury VT

Watson et al., 2016

Amidst all the ecosystem services offered by functional floodplains and wetlands, they are some of the most powerful mitigation tools there are to reduce flood risk in the face of a changing climate. The Otter Creek case study is a valuable example. Otter Creek runs north through a large wetland complex and wide floodplain from Rutland to Middlebury, Vermont. In 2011, Tropical Storm Irene devastated areas across the state. Rutland experienced its highest peak flow on record on August 28th, suffering extensive damages and flooding for the following five days. Downstream, Middlebury had a much lower peak and minor flooding (Figure 3-10).

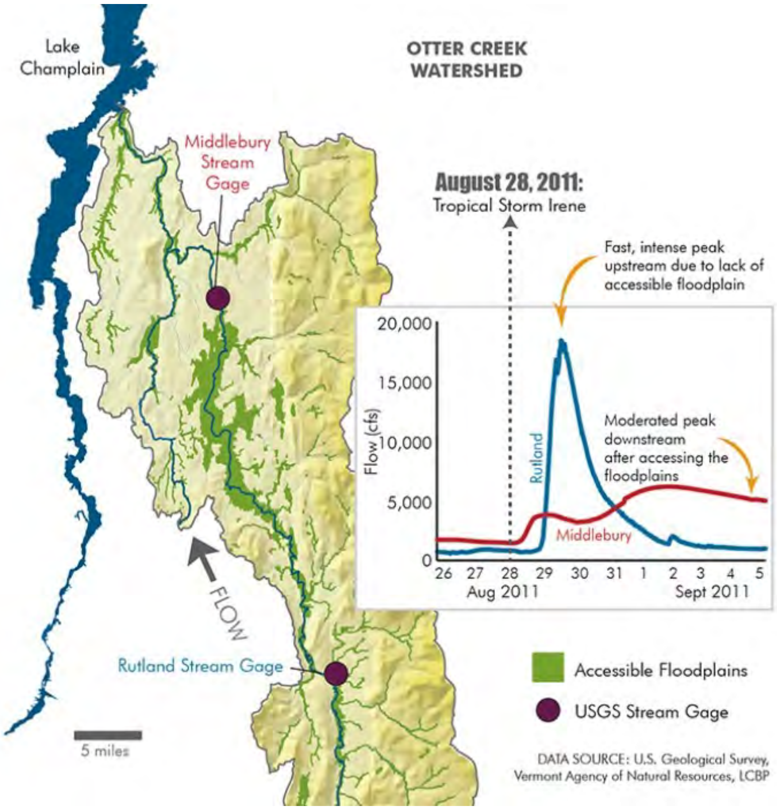
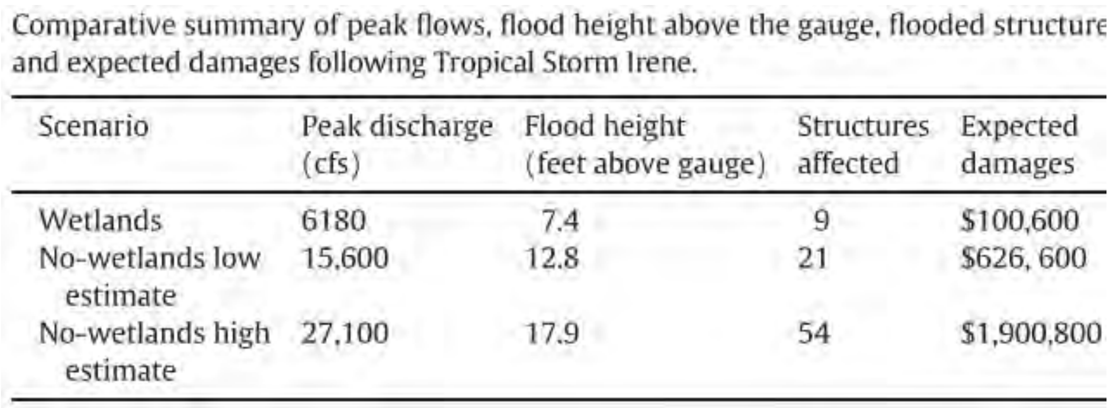


Figure 3-10. Map of Otter Creek Watershed showing locations of stream gauges at Rutland (upstream, blue) and Middlebury (downstream, red), along with hydrograph of streamflow, in cubic feet per second, experienced after Tropical Storm Irene. From https://vtwatershedblog.com/2017/02/02/celebrate-wetlands-with-others-across-the-world/

Why? Unlike many of Vermont's rivers and streams, Otter Creek is not disconnected from its floodplain. The Otter Creek watershed is primarily (60%) forested and accesses 18,000 acres of wetlands. (See Water Features and Ecological Services for background information) During Tropical Storm Irene, the floodplains and wetlands stored then gradually released the floodwater over the course of weeks rather than days. The authors of this study investigated this phenomenon further and attempt to answer two main questions:

1. What was the value of the Otter Creek wetlands and floodplains in reducing flood damage during Tropical Storm Irene in 2011?
2. Beyond this single event, what is the expected annual value of the wetlands and floodplains in mitigating flood damages?

Placing economic value on natural services can be difficult, and this study relied on hydraulic modeling and differing scenarios to achieve this. Researchers modeled two “no wetland” scenarios, which project outcomes if the wetlands and floodplains were partially or not at all contributing to mitigation (no wetlands low, no wetlands high, respectively). They compared them with the actual wetlands to determine the extent of flooding and related damages that were avoided from Tropical Storm Irene in Middlebury (see Table 3-2) Damage estimates are quite conservative because they focus on buildings that would have flooded, using property records, but omit other expenses like road damage or crop loss.



Comparative summary of peak flows, flood height above the gauge, flooded structure and expected damages following Tropical Storm Irene.

Scenario	Peak discharge (cfs)	Flood height (feet above gauge)	Structures affected	Expected damages
Wetlands	6180	7.4	9	$100,600
No-wetlands low estimate	15,600	12.8	21	$626, 600
No-wetlands high estimate	27,100	17.9	54	$1,900,800

Table 3-2. Peak streamflow discharge, flood height,

Modeling procedures were repeated for nine more historical flooding events to evaluate the benefits beyond Tropical Storm Irene. Researchers valued the flood mitigation services of Otter Creek at over $12 million dollars, accounting for over a quarter of conservation costs (equivalent to purchasing the full 18,000 acres of wetlands for conservation). The value of flood mitigation services offered by wetland and floodplains are likely to increase with climate change, as intense precipitation events are already becoming more common.

2.6.3 Social Vulnerability, Flooding and Disaster Risk Reduction

Ned Swanberg

Key Point: Development in flood hazard areas endangers those structures and the citizens that use them. This risk is unequally distributed within Vermont spatially, and skews toward socially vulnerable groups.

In Vermont over ten thousand structures are located within a high-risk Special Flood Hazard Area (SFHA) (State of Vermont, 2021). These flood risk areas, as mapped for the National Flood Insurance Program (NFIP), indicate areas with a one percent annual chance of flooding. Over the period of a thirty-year mortgage this represents more than a 1 in 4 chance of experiencing flooding at the site. Within the area are portions that experience more frequent flooding. Less frequent and larger floods will also occur and reach beyond the mapped boundaries.

Most of the damage due to flooding in Vermont is not well characterized by these data. The actual damage in Vermont is often due to the erosive power of moving water, not so much by saturation. Hence, a considerable amount of work is underway in Vermont to protect river corridors both to avoid direct damage from erosion as well as to accommodate the room needed by the channel to avoid incision, maintain functional floodplains, and to diminish and delay flood peaks.

Special Flood Hazard Areas in Vermont were first mapped in the 1970s and became the basis for municipal regulation and participation in the National Flood Insurance Program (www.msc.fema.gov). The most recent map update was in Bennington County (effective 12/2015) and portions of other counties with Digital Flood Insurance Rate Maps received updated detailed studies. Notably, none of these recent maps reflect the Vermont flood discharges of 2011. All these mapped areas include some areas with detailed engineered studies and other areas with approximate studies. Currently FEMA is undertaking flood hazard map updates in many Vermont watersheds. If funded, these maps may become generally effective around 2025.

Under FEMA mapping guidelines, the maps show the flood levels based on past flood discharges. Since the 1970s precipitation has increased, and precipitation patterns have been altered. At their best, the boundaries of the mapped Special Flood Hazard Areas portray the past and do not adequately represent the current or future conditions and risks associated with inundation.

The flood risk in the maps and data below reflect best available data from both officially digitized together with rough non-official digital maps of effective Special Flood Hazard Areas and e-911 site location data in Vermont. While these data have considerable error-bands they do allow us to broadly examine the distribution and character of flood risk in Vermont.

In Vermont, approximately 4% of all structures are within a high-risk Special Flood Hazard Area. This varies by community and can be viewed in expanded community reports. Also, very few structures within the SFHA are carrying any level of flood insurance. This level has declined to 15% after reaching a peak of nearly 25% in 2013. This decline in flood insurance uptake may reflect several factors: flood amnesia, people dropping insurance when it is not specifically required by a lender, and the rising cost of flood insurance premiums and fees. Several private insurance companies have recently begun to offer flood insurance in Vermont. In October 2021 FEMA rolled out a fundamentally new method of calculating flood insurance premiums as Risk Rating 2.0. These changes may significantly change flood insurance uptake, household resilience and community flood recovery.

Figure 3-11. Percentage of Vermont Structures within the Special Flood Hazard Area (SFHA) with an NFIP Policy in force (VT DEC, 2015). Based on FEMA Community Information Systems (CIS) data on Policies in Force (PIF) and e911 points in SFHA.

Concentrations of Risk

Of the roughly 12,000 structures located in the SFHA, the communities with the highest concentrations include the Town of Bennington, Barre City, Brattleboro, and Montpelier. Some of the concentrations reflect lake shore development and approximate mapping.

Table 3-3. Communities in Vermont with 100 or more structures located in the Special Flood Hazard Zone. Data based on e911 site locations and non-official statewide flood hazard area mapping.

Town	**Structures in the SFHA**
BENNINGTON	476
BARRE CITY	342
BRATTLEBORO	325
MONTPELIER	312
SAINT ALBANS TOWN	283
MORGAN	264
WINDSOR	249
ALBURGH	203
LUDLOW	190
WOODSTOCK	190
DERBY	181
WATERBURY	175
SWANTON	172
POWNAL	168
NORTH HERO	162
BERLIN	161

Town	**Structures in the SFHA**
FERRISBURGH	141
BARNET	137
RUTLAND CITY	135
LUNENBURG	131
JOHNSON	126
JAMAICA	120
LYNDON	117
WELLS	114
DOVER	108
NORTHFIELD	108
SAINT JOHNSBURY	107
RICHMOND	100
WILMINGTON	100

Structures at Risk and Social Vulnerability

Among the structures most vulnerable to direct damage from flooding are structures with below grade basements (common in Vermont), single story structures, and manufactured homes. The presence of a basement, or the number of building stories is difficult to determine from remote sensing data. Manufactured Homes (or Mobile Homes) represent over 10% of the structures in the high-risk flood hazard area (Baker et al., 2014). Manufactured homes are particularly susceptible to damage from inundation. Additionally, since manufactured homes are also low-cost structures, they easily can experience total loss or “Substantial Damage” from inundation: where repair costs exceed 50% of the value of the structure.

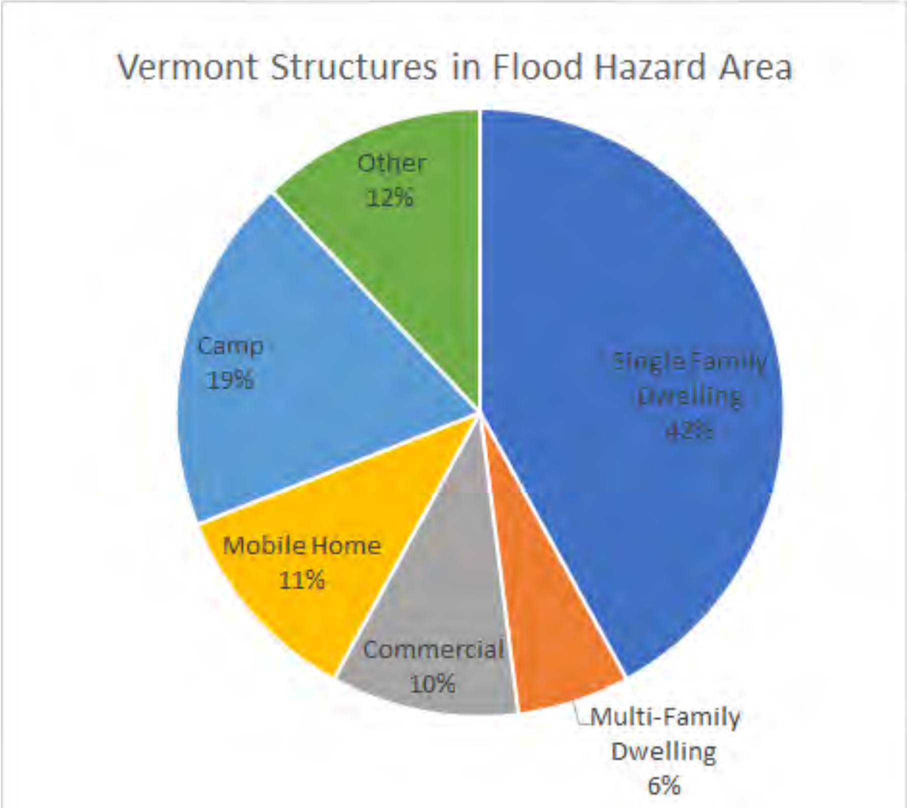


Figure 3-12. Structures located in the flood hazard area throughout Vermont, by housing type. Data from Flood Ready Vermont.

Social vulnerability is defined as “the potential negative effects on communities caused by external stresses on human health”, which includes natural or human-caused disasters and disease outbreaks (CDC/ATSDR, 2021). “Reducing social vulnerability can decrease both human suffering and economic loss” (CDC/ATSDR, 2021). Spatial analysis has found national hotspots where flood exposure and social vulnerability combine, with three characteristics that are significant in these hotspots: manufactured homes, and Black or Native American populations (Tate et al., 2021). The Centers for Disease Control and Prevention (CDC) have published a Social Vulnerability Index compiling US Census block data around four themes (socio-economic, household, race/ language, and housing type) using 15 census variables (CDC/ATSDR, 2021).

The choropleth map in Figure 3-13 shows the four CDC themes as transparent overlays. These four themes (Table 3-4) are prominent in the northeastern portion of Vermont and other municipalities.

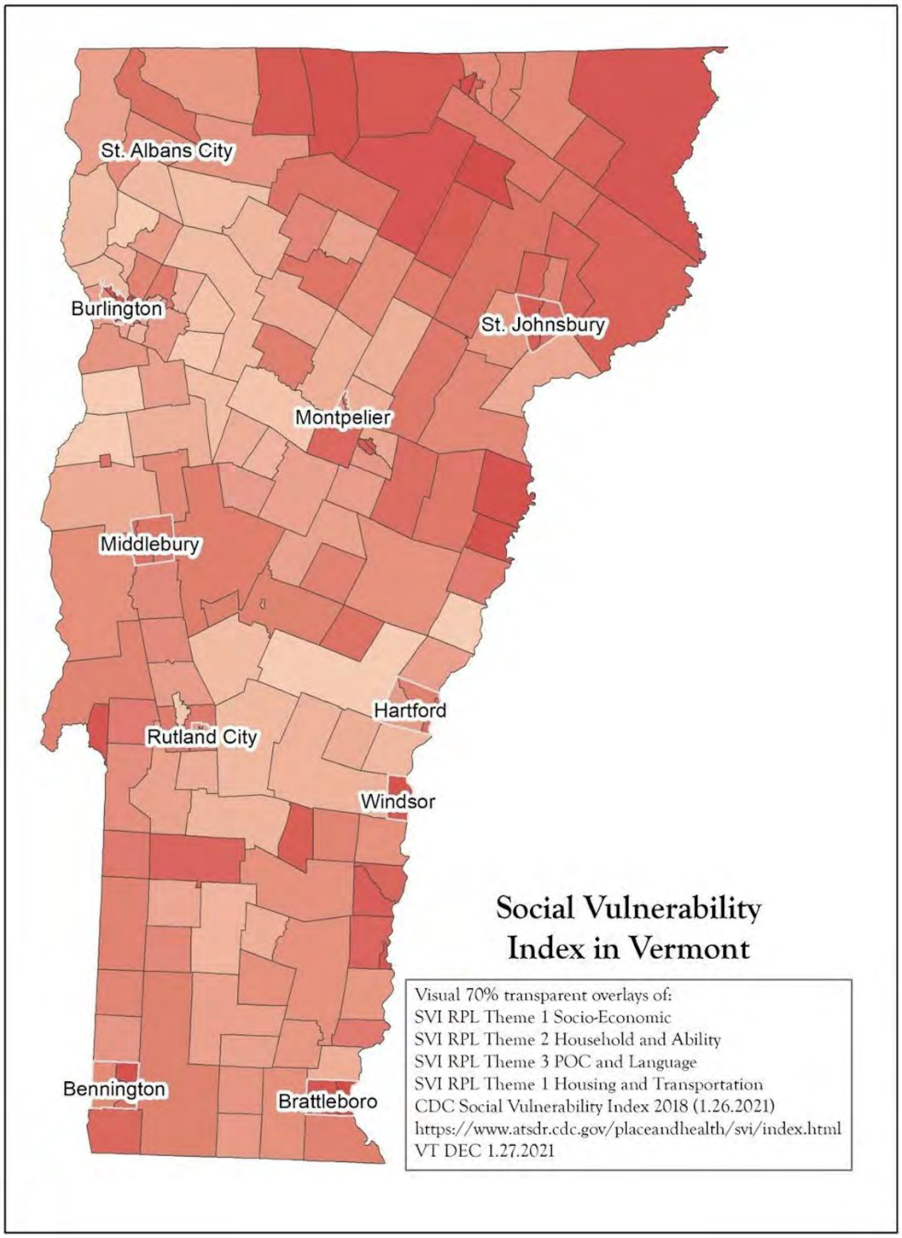


Figure 3-13. Map showing concentrations of social vulnerability in Vermont (light red to dark red), as defined by the CDC Social Vulnerability Index.

Table 3-4. Table of four themes used to assess social vulnerability in CDC Social Vulnerability Index, with factors belonging to that theme. From https://www.atsdr.cdc.gov/placeandhealth/svi/

CDC Social Vulnerability Themes	**Social Factors**
Socioeconomic status	below poverty, unemployed, income, no high school diploma
Household composition and disability	aged 65 or older, aged 17 or younger, older than 5 with a disability, single-parent households
Minority status and language	minority, speak English "less than well"
Housing type and transportation	multi-unit structures, mobile homes, crowding, no vehicle, group quarters

Figure 3-14 includes an additional transparent municipal layer indicating the percentage of structures in the flood zone without flood insurance, and the locations of manufactured homes in the flood zone.

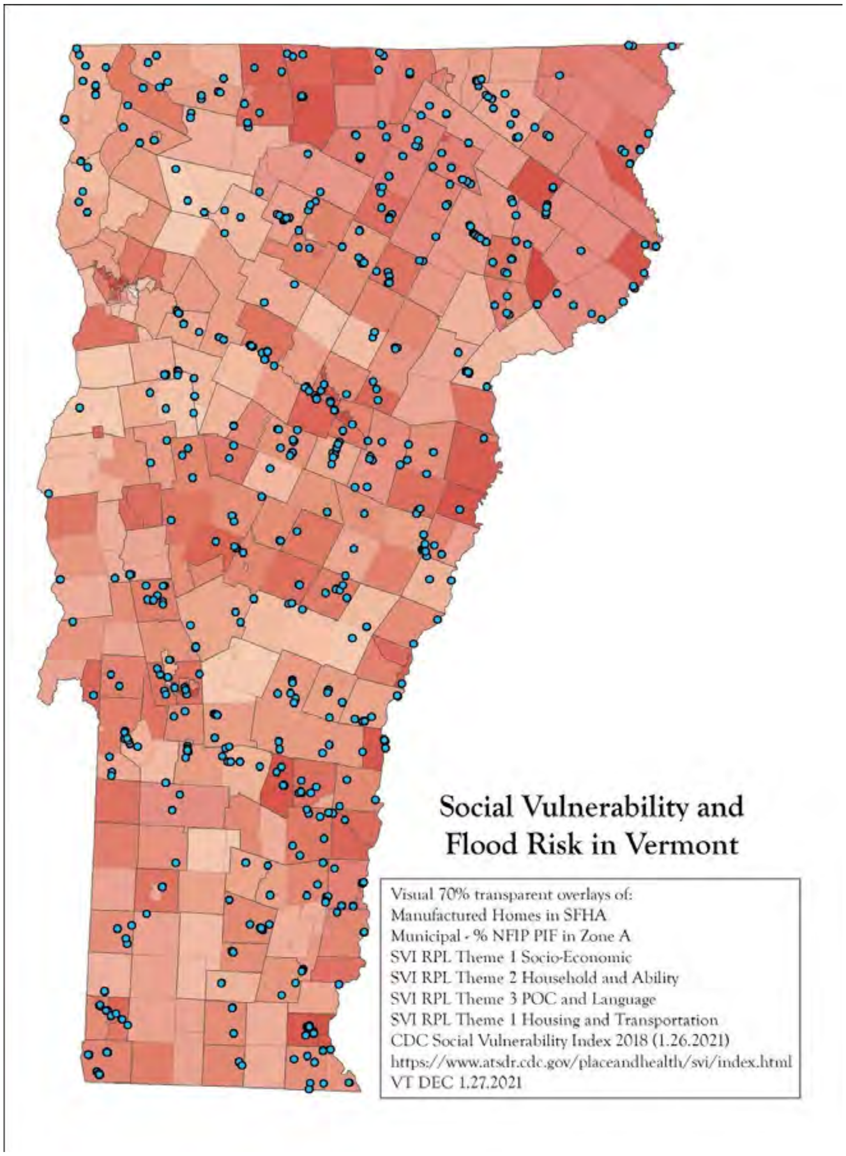


Figure 3-14. Social Vulnerability and Flood Risk in Vermont.

In 2020 FEMA began a process of looking at social equity in its hazard mitigation programs such as Building Resilient Infrastructure and Communities (BRIC); the successor to the Pre-Disaster Mitigation Grant Program. At this time there is a need for access to safe affordable housing in Vermont including socially vulnerable people living in high-risk flood hazard areas.

Box 3.3 Spatial targeting of floodplain restoration to equitably mitigate flood risk

Gourevitch et al., 2020

Floodplain restoration enhances communities' resilience to flooding and climate change. It can be difficult to determine where to implement it, and budgets are limited, so localized flooding data at fine spatial scales supports targeted decision-making. A second challenge is incorporating social vulnerability to ensure equitably distributed benefits from restoration projects and risk of flood exposure.

Lewis Creek is a small watershed in eastern Vermont that is vulnerable to flooding due to mountains upstream. 41 properties are located in the SFHA, many of which are manufactured or mobile homes. Flood damages were estimated based on hydraulic modeling for 1%, 4%, 10%, and 50% annual chance flood intervals. They are heavily skewed towards lower-income properties, with the bottom quartile incurring >90% of damages and 25 mobile homes incurring damages 5x their appraised value. A range of restoration scenarios were identified to account for varying budgets.

199 potential restoration sites were identified, but benefits could be maximized by revegetation of wetlands or floodplains in only a few of them. This demonstrates the benefits of spatially-targeted data in terms of ecosystem services. However, the distribution of avoided damages tended to favor more expensive buildings/ higher-income property owners, and giving more weight to equity in choosing restoration projects does not highly change the outcome for this case study. The authors suggest that this may not be the same everywhere, and compensatory mechanisms should be in place so lower-income property owners can be compensated for damages and value of avoided damages. Overall, this case study is an excellent example of the inequitable weight of flood exposure in Vermont communities.

2.6.4 Stream-Crossing Infrastructure

Key Point: Stream-crossing infrastructure suffers extensive damage due to flooding. Bridges and culverts are vulnerable to failure during high-flow conditions, especially when outdated or undersized.

Road-stream crossing infrastructure is some of the most vulnerable to flooding damage because these structures intersect the river corridor. Depending upon the structure design, stream crossings and their road approaches can impound floodwaters, constrict flows, and induce debris jams.

During Tropical Storm Irene in 2011, about 480 bridges and 960 culverts were damaged, in addition to >2500 miles of road (VT Emergency Management, 2018). Since then, the State of Vermont has modified stream crossing standards for culverts and bridges to accommodate the bank-full discharge and consider the geomorphic condition of the reach. Statewide assessments of crossing structure dimensions and conditions has led to systematic and ongoing efforts to bring vulnerable structures into a compatible condition.

Small under-the-road culverts (away from streams) are also vulnerable to damage from high flows including localized thunderstorms. Undersized and clogged culverts can lead to considerable road damage. Many Vermont roads were located in immediate proximity to streams and rivers following historical patterns including those of early lumber operations that straightened steep mountain brooks (Kline & Cahoon, 2010). This legacy pattern leaves hilly Vermont particularly exposed to considerable damage at crossing structures, roads, and nearby buildings from all sizes of high flows and flash floods.

Some sites are simply poorly located to host a stream crossing (Bates & Kirn, 2009; Gillespie et al., 2014). Planners should determine the necessity of a structure when planning to build or replace it; critical structures include those with high-volume traffic or emergency service routes (Austin & McKinley, n.d.). For more information on criticality and flood vulnerability in the state transportation network, see VTrans Statewide Highway Flood Vulnerability and Risk Map in Resources.

2.6.5 Flood Risk for Structures

Keeping in mind how critical a structure is, there are further issues considering heightened risk of flood exposure: outdated structures, undersized structures, and resilient engineering standards.

Outdated Infrastructure

Outdated stream-crossing infrastructure is common in Vermont and throughout New England. Over 20% of Vermont's bridges are functionally obsolete and do not meet current engineering standards. With increases in precipitation, high flows, and severe storm events due to climate change, these outdated features are vulnerable to failure. Many bridges and culverts have reached the end of their useful life, and are not built to modern higher-resilience standards. With limited funding, they can exceed their intended lifespan by decades, while incurring repetitive costs for maintenance, operations, and repairs (American Society of Civil Engineers Vermont Section, 2019). While the oldest structures are not necessarily the ones that need immediate repair or replacement, this analysis stays relevant for incoming decades as Vermont evaluates how to build flood mitigation features into its transportation network.

Many of Vermont's bridges were built from the 1930s to 1970s; they were designed for a useful life of 50 years (American Society of Civil Engineers Vermont Section, 2019). A culvert's useful life is more variable depending on building material and environmental factors, from 25 to over 100 years. A typical steel culvert using the traditional hydraulic design approach tends to last 25-50 years (Gillespie et al., 2014). In New York State, for example, the average useful life of a culvert is 56 years (Molinas & Mommandi, 2009).

Current inspection information for bridges and culverts was used to produce Figures 3-15 and 3-16. This inventory is maintained by the Vermont Department of Transportation, but does not always stay up to date or include every municipality. The year built is divided into equal intervals based on the useful life of the structure (i.e. a structure built before 1970 with a useful life of 50 years has reached the end of it by 2020). If the structure was replaced, the year of reconstruction was used to accurately reflect the age of the structure. Short structures (6-20 feet in length) are primarily culverts, while long structures (>20 feet) tend to be bridges.

There are bridges and culverts in both datasets, which are available from the VT Open GeoData portal.

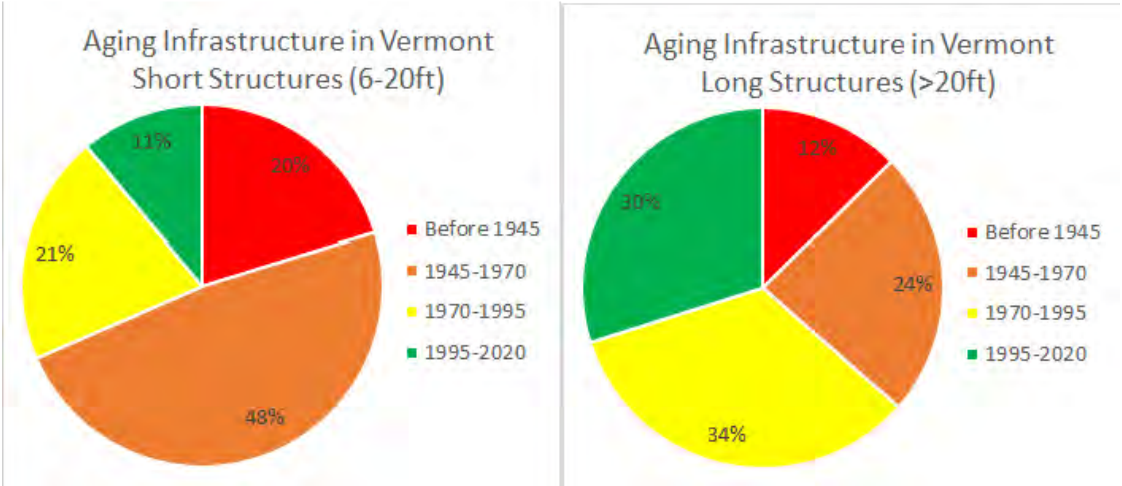


Figure 3-15. Pie charts of age breakdown for short structures (left) and long structures (right) throughout the state of Vermont.

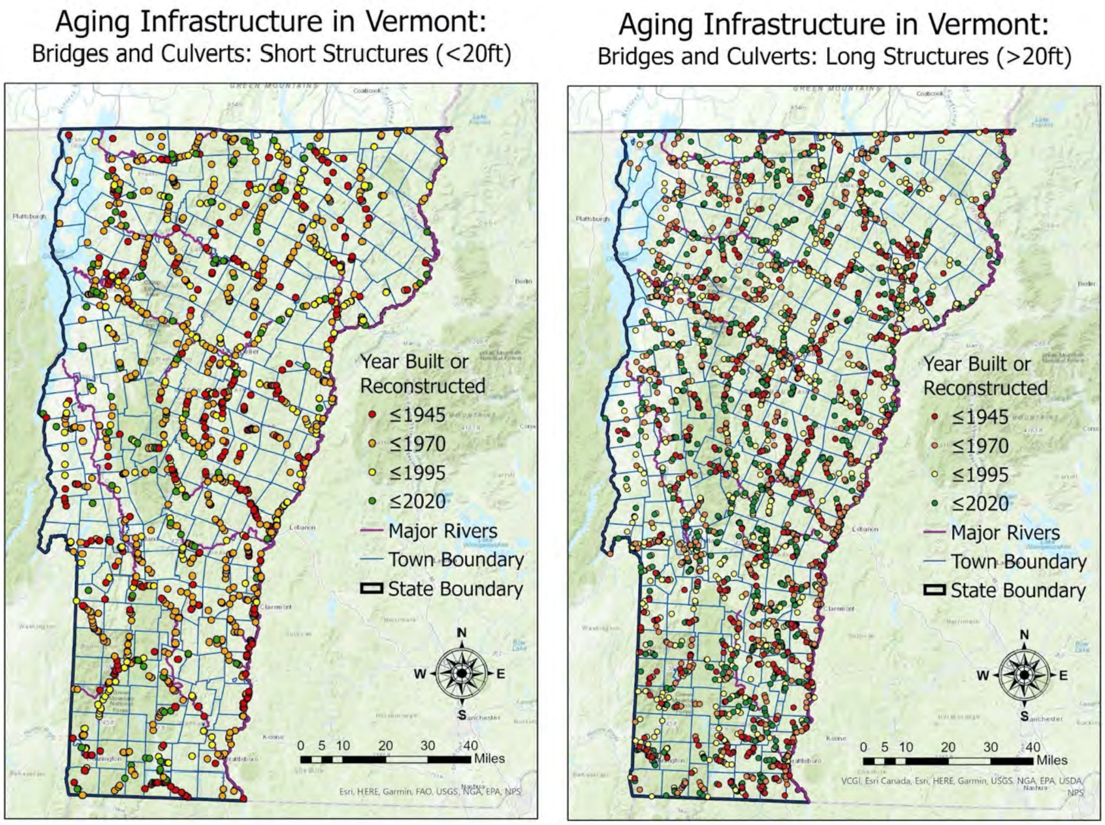


Figure 3-16. Spatial distribution of bridges and culverts in Vermont. Many stream-crossing structures (points) follow major river stems (purple line).

These figures emphasize the outdated and vulnerable nature of Vermont's current infrastructure network. On the assumption that the useful life of these structures is about 50 years (American Society of Civil Engineers Vermont Section, 2019; Gillespie et al., 2014), that means that 68% of short structures and 36% of long structures in Vermont are past due for replacement (orange and red categories).

Undersized Infrastructure

Culverts and bridges are undersized when they do not appropriately fit the size of the channel, hindering their ability to manage streamflow, pass debris, and allow fish passage. High-magnitude precipitation events are becoming more common in Vermont (Guilbert et al., 2015), and undersized culverts exaggerate the impacts. Water is channeled through an outlet that is too small, creating powerful flows. During storm events, undersized culverts can fail when floodwaters exceed the hydraulic capacity of the culvert, or debris and/or sediments plug up the culvert (Gillespie et al., 2014).

Many undersized culverts result from traditional hydraulic capacity design, made to handle a certain flood, like with an annual 1%, 2%, or 4% chance of occurrence. Discharge estimates used in these designs have standard error estimates over 40%. They are also based on historic data and do not incorporate the increasing precipitation trends observed in the Northeast nor climate change projections (Gillespie et al., 2014). By defining the structure's design in this way, channel size is disregarded, resulting in undersized culverts that are vulnerable to failure. When a stream-crossing structure failed, it was usually replaced in-kind, or with a structure that has the exact same design, until recently, when the damage incurred during Tropical Storm Irene forced changes in engineering standards. Replacement costs after failure are supplemented by damages to nearby property and roads and can be incurred multiple times in the culvert's lifetime (Gillespie et al., 2014). With many undersized culverts remaining throughout Vermont, they are left vulnerable to high flows, heavy storms, and extreme events. As heavy precipitation increases in Vermont, alternatives need to be adopted that can endure future conditions.

Engineering Alternatives and Solutions

Stream simulation design is an ecologically-based engineering alternative that has gained ground in recent years in Vermont (Bates & Kirn, 2009). It aims to simulate, as closely as possible, the characteristics and dimensions of the natural channel, acting as a solution to undersized structures while improving wildlife passability and ecological connectivity (Gillespie et al., 2014).

The benefits of the stream simulation design approach go beyond aquatic organism passage and stream connectivity (Austin & McKinley, n.d.; Bates & Kirn, 2009; Gillespie et al., 2014; Christiansen et al., 2014). The size of the culvert must match or exceed that of the channel, so that floodwaters and debris can pass through more easily, reducing risk of failure from flooding and erosion. Culverts built by stream-simulation design can achieve lifetimes double that of traditional hydraulic capacity design; ranging from 50-75 years rather than just 25-50 years (Christiansen et al., 2014). The Vermont Department of Fish and Wildlife has proposed incorporating stream simulation design concepts into Vermont's statewide infrastructure system and construction standards (Kirn, 2016).

Replacing outdated and undersized infrastructure seems a costly problem, but it is also a valuable investment and opportunity. It is inefficient to replace and repair infrastructure with the same designs that cannot withstand flooding failure or offer resilience to climate change, especially since they can fail multiple times within a lifespan. Rather, there is an opportunity to assess when and where these structures are necessary and incorporate projections and resilience into plans to replace them. Anthropogenic climate change has invalidated the historical data and assumptions that form the foundation of their design. Alternatives like stream simulation design offer longevity, economic return on investment, and wildlife suitability. Taking a proactive approach may be key to avoiding the sort of catastrophic outcomes of Tropical Storm Irene.

See Green Mountain National Forest case study as an example of engineering alternatives (Forest Chapter, section 2.5.5).

Box 3.4 Local Success in Brandon, Vermont

In 2011, Tropical Storm Irene flooded downtown Brandon in Addison County, Vermont, due to the overtopping of the Neshobe River that is constricted as it runs through the town. Many buildings were damaged, and one was completely destroyed. Brandon incurred an estimated $800,000 in August, 2011 (Brandon, VT Community Report, 2015). Municipal stakeholders reacted quickly, realizing the need for more resilient infrastructure to protect the town from future devastation.

FEMA’s State Hazard Mitigation Program allocated $2.55 million to design and construct an overflow culvert to divert excess water from the Neshobe away from downtown property. Construction was completed in May 2017, and on July 1st, just forty days later, a major storm hit Addison County. Downtown Brandon experienced no flood damages -- a successful return on investment (DuBois & King, Inc., 2017).

Figure 3-17. Source: https://www.dubois-king.com/dk-flood-mitigation-design-delivers-first-major-storm-irene/

2.7 RESOURCES FOR COMMUNITY MEMBERS AND PLANNERS

These are Vermont resources for interested parties to find hyper-local information. Many of these resources allow one to search by address or municipality to get specific information that is most relevant to them. These resources do not always have complete data coverage or are not always up to date. However, these resources allow a user to apply the kinds of information presented in the VCA 2021 at fine spatial scales.

2.7.1 Building in the Floodplain

National Flood Insurance Program, Floodplain Management Requirements. Accessed online 21 May 2021 at https://www.fema.gov/pdf/floodplain/nfip_sg_unit_5.pdf

State of Vermont, Flood Training Protection Tools, Build it Safe. Accessed online 31 May 2021 at https://floodtraining.vermont.gov/protection-tools/build-safe

State of Vermont, Vermont Flood Hazard Area and River Coordinator Rule. Access online 31 May 2021 at https://dec.vermont.gov/sites/dec/files/documents/wsmd-fha-and-rc-rule-adopted-2014-10-24.pdf

2.7.2 Flood Vulnerability

State of Vermont, Flood Ready Atlas (maps.vermont.gov). Accessed online 31 May 2021 at tinyurl.com/floodreadyatlas

- Flood hazard areas (from FEMA)
- Participating communities in insurance programs

U.S. Government, FEMA Flood Maps. Access online 31 May 2021 at https://msc.fema.gov/portal/home

- FEMA maps for localized flood data
- Search by address
- Problem: many flood hazard maps are outdated, and some areas that are mapped outside the flood zone are still at risk (as with Hurricane Irene)

State of Vermont, Flood Ready Vermont Community Reports. Accessed online 31 May 2021 at https://floodready.vermont.gov/assessment/community_reports#Expanded

Use Flood Ready Vermont Community Reports to generate information on your community's:

- Insurance information and participation in ERAF incentive program
- Number of structures in the flood zone
- Compliance with road and bridge standards
- Compliance with river corridor protections

State of Vermont, Flood Training. Accessed online 31 May 2021 at https://floodtraining.vermont.gov/

This provides in-depth, yet accessible, explanations of key flooding concepts like:

- Floodplains and River Corridors
- Special Flood Hazard Areas
- No Adverse Impact

International Joint Commission, International Lake Champlain-Richelieu River Study Board at https://www.ijc.org/en/lcrr

This is an ongoing project to assess causes, impacts, risks and potential solutions to flooding in the Lake Champlain-Richelieu River Basin.

2.7.3 Infrastructure

State of Vermont, Department of Environmental Conservation. River Management Principles, Practice, and Training. Accessed online 2 October 2021 at https://dec.vermont.gov/watershed/rivers/river-management#principles

State of Vermont, Agency of Transportation. Statewide Highway Flood Vulnerability and Risk. Accessed online 31 May 2021 at https://vtrans.vermont.gov/planning/transportation-resilience/statewide

- Flood vulnerability: culverts, bridges, and road embankments that are vulnerable to erosion, deposition, and inundation
- Transportation criticality: travel demand and how important that structure is to the transportation network
- Flood Risk: combines vulnerability and criticality to prioritize action items

State of Vermont, Vermont Culverts. Accessed online 31 May 2021 at vtculverts.org. Allows users to access an interactive map interface. Find culvert and bridge structures current conditions (i.e. failures).

Vermont Fish and Wildlife Stream Crossing Handbook
https://vtfishandwildlife.com/sites/fishandwildlife/files/documents/Learn%20More/Library/REPORTS%20AND%20DOCUMENTS/AOP/AOP%20HANDBOOK.pdf

2.7.4 Wetlands

State of Vermont Agency of Natural Resources:

Wetlands Inventory. Accessed online 31 May, 2021 at https://anrmaps.vermont.gov/websites/WetlandProjects/default.html

Wetland Screening Tool. Accessed online 31 May 2021 at https://anrmaps.vermont.gov/websites/wetlandScreening/

Landowner's Guide to Wetlands. Accessed online 31 May 2021 at https://dec.vermont.gov/sites/dec/files/wsm/wetlands/docs/wl_Am_I_in_a_Wetland.pdf

Wetland Restoration. Accessed online 31 May 2021 at https://dec.vermont.gov/watershed/wetlands/protect/restore

2.7.5 Stream gauge records

Streamflow records shown in the text were standardized to 1960-present. Here, we include the full observational record for each site. Trends are statistically significant ($p<0.05$, Mann Kendall) for all sites' entire period of record (Figure 3-18). P-values are given in Table 3-5 along with USGS site identification numbers and place names.

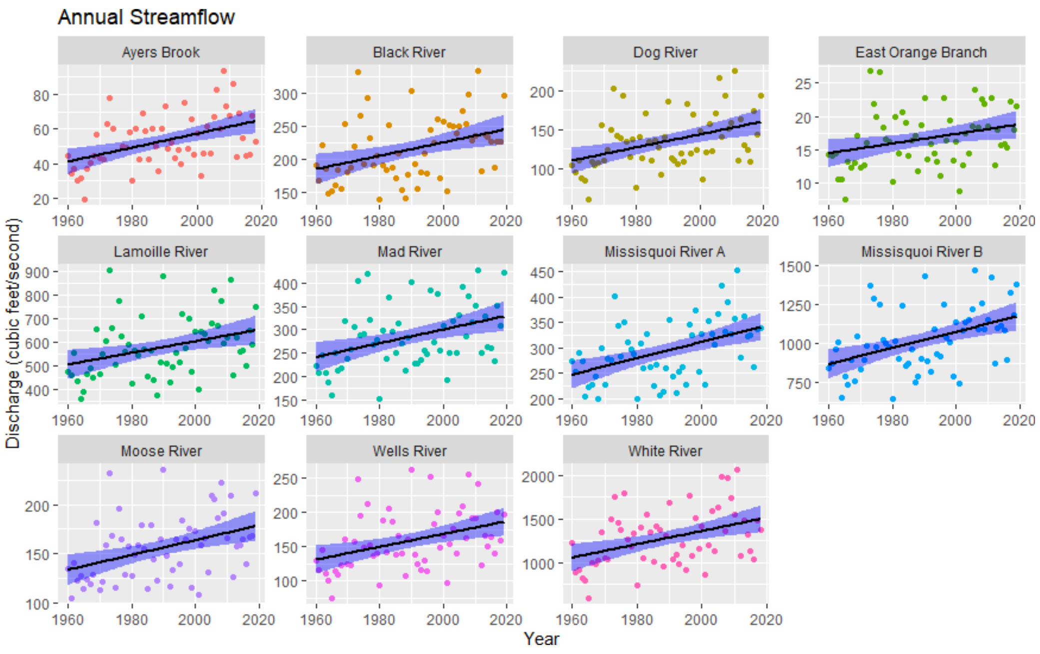


Figure 3-18. Average annual streamflow over time at 11 streamflow gauges in Vermont. Linear trendlines with 95% confidence intervals.

Table 3-5. Sites used in streamflow analysis and p-values obtained from Mann-Kendall test of time series by site.

USGS Site ID	Site Name	Mann Kendall, p-value (full record)				
		Annual	Winter	Spring	Summer	Autumn
01134500	MOOSE RIVER AT VICTORY	0.00195	0.00049	0.5645	0.01794	0.003
01139000	WELLS RIVER AT WELLS RIVER	0.00171	0.0003	0.558	0.00194	0.00368
01139800	EAST ORANGE BRANCH AT EAST ORANGE	0.02846	4.029e-5	0.2411	0.00113	0.01462
01142500	AYERS BROOK AT RANDOLPH	0.00073	4.268e-5	0.9899	0.00037	0.00373
01144000	WHITE RIVER AT WEST HARTFORD	0.01832	9.131-05	0.3412	0.00878	0.0066
04287000	DOG RIVER AT NORTHFIELD FALLS	0.00521	0.00076	0.3331	0.00013	0.00996
04288000	MAD RIVER NEAR MORETOWN	0.00018	8.631e-5	0.3214	0.00033	0.00248
04292000	LAMOILLE RIVER AT JOHNSON	0.00064	1.633e-5	0.4224	0.009	0.0032
04293000	MISSISQUOI RIVER NEAR NORTH TROY	0.00051	0.00011	0.9368	0.00086	0.02534
04293500	MISSISQUOI RIVER NEAR EAST BERKSHIRE	0.00052	1.037e-5	0.7892	0.00372	0.00397
04296000	BLACK RIVER AT COVENTRY	0.00601	2.48e-5	0.5357	0.0312	0.01557

2.8 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

Traceable Account 1.				
Key Message 1: Due to extreme variation in precipitation with our changing climate, periods of prolonged dry-spells and drought, coupled with higher water usage in snowmaking and agriculture could exacerbate low water availability.				
Confidence level	***High***			
Finding	Increases in overall and heavy precipitation have been observed. Betts 2017 suggests that dry spells will become more common, but an increasing trend in drought has not been assessed. Increased demand for snowmaking is evident due to decreases in natural snowfall and increased temperatures, and multiple sources concur that irrigation demand will increase as well.			
References	Guilbert et. al 2014; Guilbert et al. 2015	NCA 2018; Betts 2017	Wilson et al., 2018	Schaible & Aillery, 2017; Wolfe et al., 2018

Traceable Account 2.				
Key Message 2: Increases in overall precipitation and extreme precipitation have caused streamflows to rise since 1960. Climate change will further this pattern, although the overall increase in streamflow comes with disruptions in seasonal flows cycles.				
Confidence level	***Very High***			
Finding	Increases in precipitation and streamflow are evident in several sources and within the analyses produced by this paper. Spring seasonal streamflow did not exhibit significant change over time, despite increases in overall precipitation, suggesting disruption to seasonal flow cycles.			
References	Hodgkins & Dudley, 2011	Hodgkins 2010	Dudley et. al 2017	

Traceable Account 3.				
Key Message 3: Increases in heavy precipitation jeopardize water quality in Vermont. Storms produce large runoff events that contribute to erosion and nutrient loading. Combined with warm temperatures, this creates favorable conditions for cyanobacteria blooms.				
Confidence level	***High***			
Finding	Sediment and nutrient loading undoubtedly cause poor water quality in Vermont. Heavy precipitation events, which are increasing under climate change, contribute more to these processes than smaller events. While increases in cyanobacteria blooms have not been directly observed, there is an established relationship between nutrient enrichment and cyanobacteria.			
References	LCBP, 2015	Stockwell et. al 2020	Smeltzer et al., 2012	

Traceable Account 4.				
Key Message 4: Increased occurrence of high streamflows increase the risk of flooding that causes damages to many roads and crossing structures. Risk reduction requires addressing outdated and unfit structures.				
Confidence level	***Very High***			
Finding	Flooding causes damage to structures, stream crossings, and roads, as seen after Tropical Storm Irene. There is concurrence about the increased risk of flooding and the lack of suitability of Vermont's stream-crossing infrastructure in terms of flooding resilience.			
References	LCBP, 2015	Guilbert et al., 2015	Gillespie et al., 2014	

Traceable Account 5.				
Key Message 5: Nature-based solutions are an effective, low-cost approach to climate change adaptation. River corridor, floodplain, and wetland protection dampen flood impacts and improve water quality along with green infrastructure.				
Confidence level	***Very High***			
Finding	There are several sources and case studies that demonstrate the effectiveness of river corridors, floodplains, and wetlands in improving climate resilience, particularly through flooding protection and water quality improvement.			
References	Watson et al., 2016	Gourevitch et al., 2020	Lester et al., 2019	

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3 FISH AND WILDLIFE IN VERMONT

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3.1 KEY MESSAGES

1. As climate change worsens, 92 bird species of Vermont, including the iconic common loon and hermit thrush, are expected to disappear from the landscape within the next 25 years.
2. Increasing warming trends are expected to result in an increase in white-tailed deer population and a mirrored decrease in moose population, which may have long-term impacts on Vermont's forest composition. Managing social systems (e.g. hunting) to account for changing public tolerance and demand for deer may provide one avenue to minimize this risk if undertaken proactively.
3. As warming trends reduce the severity of winters, the subsequent warming waters will have adverse effects on lake and river systems, including increased risk for harmful algal blooms (HABs) and reduced overall biodiversity and health in lake ecosystems.

3.2 BACKGROUND

Anthropogenic climate change has had a warming influence on the planet since the 1750s that has resulted in increased global mean temperature. As a result, Earth has seen shifts in annual precipitation, average seasonality, and a host of other changes. These shifts affect the environment in several ways, and the complex interactions that occur can often seem opaque. This is especially true when considering how climate change may affect organisms other than humans. Without proper monitoring and study of organisms, it is difficult to parse out the full effect that climate change may have on different species, as well as the full impact that policy plans or management strategies may have as a proactive plan to buffer those shifts. Current research is attempting to address these issues, and many important interactions have been documented and observed to link climate change to organism behavior and survival. A few of these interactions are listed below as they are often important indicators for fish and wildlife.

3.2.1 Annual Precipitation and Rainfall Events

Reports and monitoring efforts across Vermont have recorded ever-increasing levels of precipitation annually since the early 1900s, with average annual precipitation across all seasons seeing significant positive trends. Since 1960, summer precipitation in Vermont has seen the fastest increase with 0.5 inches per decade, winter and fall each with 0.3 inches per decade, and spring with 0.2 inches per decade (see Climate Change in Vermont chapter). This impacts a variety of aquatic and terrestrial organisms that rely on Vermont's riverine and lake systems for shelter, reproductive cycles, and resources.

3.2.2 Increasing Annual Mean Temperature and Winter/Spring Seasonality

Based on current climate projections, winter temperatures will gradually increase, reducing winter severity and shortening the winter season itself. This will have a negative effect on the total ice cover of water bodies. Changes in winter seasonality have also resulted in shifts in animal community structures to more warm-adapted species. **Vermont's annual average temperature has increased by almost 2**°F since 1900, but winter temperatures have increased 2.5 times faster than annual temperatures over the last 60 years (see Climate Change in Vermont chapter).

3.2.3 Land-Use Changes

As organisms are intrinsically tied to their habitat, anthropogenic climate change through urbanization, forest clearings, and reforestation post-agricultural abandonment has a direct effect on their overall fitness and ability to survive in their natural habitats. Increasing urbanization in montane areas and undeveloped land leads to issues of habitat loss and habitat fragmentation, both of which heavily impact biodiversity and ecological processes within a given ecosystem. This applies to both terrestrial and aquatic species, with road and dam infrastructures resulting in a variety of consequences for vulnerable species.

3.2.4 Phenological Interactions

In response to large-scale warming of their environments, many organisms are forced to shift their distributions and seasonal interactions, such as phenological events of flowering, breeding, migrating, or growing. Vermont is already experiencing increased temperatures, with average winter temperatures increasing 3.08°F since the 1960s (see Climate Change in Vermont chapter). Historical observations show the freeze-free period (number of consecutive days with minimum temperature above 28°F) has increased by 9.0 days per decade since the 1990s (see Climate Change in Vermont chapter). Increases in winter temperature and overall reduction in winter severity can lead to dramatic shifts in seasonality, which can be a considerable obstacle for wildlife with life histories that closely follow local climate patterns. Issues with phenological interactions may occur in species with narrow breeding times or migration patterns, as they are often reliant on complex interactions with organisms from other trophic levels in order to function properly. Migratory birds rely on booms in insect populations during the spring to recover from the physical strains of traveling and to support reproductive strategies. When the timing of insect emergence does not coincide with the arrival of migratory birds, this can often lead to phenological mismatch, where those birds are unable to take full advantage of the insect boom and may starve or fail to reproduce. As such, birds, insects, and fish are often susceptible to shifts in phenology.

3.3 INSECTS: POLLINATORS AND FOREST PESTS

Insects are often overlooked when studying climate change, whether that is due to the difficulties in gathering appropriate data on such small organisms, or preconceptions that insects play less of a role or are less valuable compared to larger, more charismatic species like birds and larger ungulates (Polgar et al., 2013). In fact, insects can provide a variety of ecosystem functions that largely go unnoticed by humans. Gardens and fields are heavily reliant on pollinators to initiate the growth of flowers and fruit-bearing plants, and caterpillars are the primary source of food for migratory birds recovering after their long flights. Insects are also extremely responsive to changes in their environment, and climate change effects have drastic impacts on their survival. In order to fully capture the extent of climate change, it is important to acknowledge the widespread effects that it will have and how it might affect humans.

3.3.1 Pollinators: Bees

Worldwide, bees are considered one of the most important pollinators, as they provide crucial pollination to fruit-bearing plants and flowers, and have an immense impact on agriculture and food systems. Within Vermont, close to 275 species of bees have been found, with most of them “solitary bees” that do not have colonies like honey bees but still serve as pollinators. These native bees are often more valuable as pollinators compared to the more well-known honey bee due to their wider visitation range and pollination activity. Their contribution has widespread effects on wildlife that rely on fruits, such as turkey, moose, and deer.

Concerns for bees stem from recent reports of commercial honey bee colony collapses. Current studies in Vermont have corroborated many of the indications by population trends: that pollinators are declining nationwide and are at risk of disappearing. A bumble bee survey conducted in 2012 found that of the 17 major bumble bee species commonly found in Vermont, 4 were not detected and 4 showed significant declines (Richardson et al., 2017). One major factor for these declines is anthropogenic impacts on bee species, especially agriculture.

Agricultural practices can disrupt bee populations on multiple different scales, from habitat degradation, farm management practices, pathogens, and climate change. Bee communities are heavily influenced by the surrounding landscape and the management practices employed there. Intensive farm management practices can often intensify the negative effects of landscape simplification (Nicholson et al., 2017). Less intensively managed farms had more instances of bee visitations and more diverse communities of bee species.

On a larger scale, climate change is also having adverse effects on bees. Warming temperature trends are predicted to affect bees through phenological mismatch. As the warming seasons result in earlier spring times, there may be a disconnect that occurs between the bees and the plants, as the bees may become active later in the season compared to the plants they would have visited (Memmott et al., 2007). Figure 4-1 highlights the impact that warmer temperatures under climate change may have on phenological mismatching.

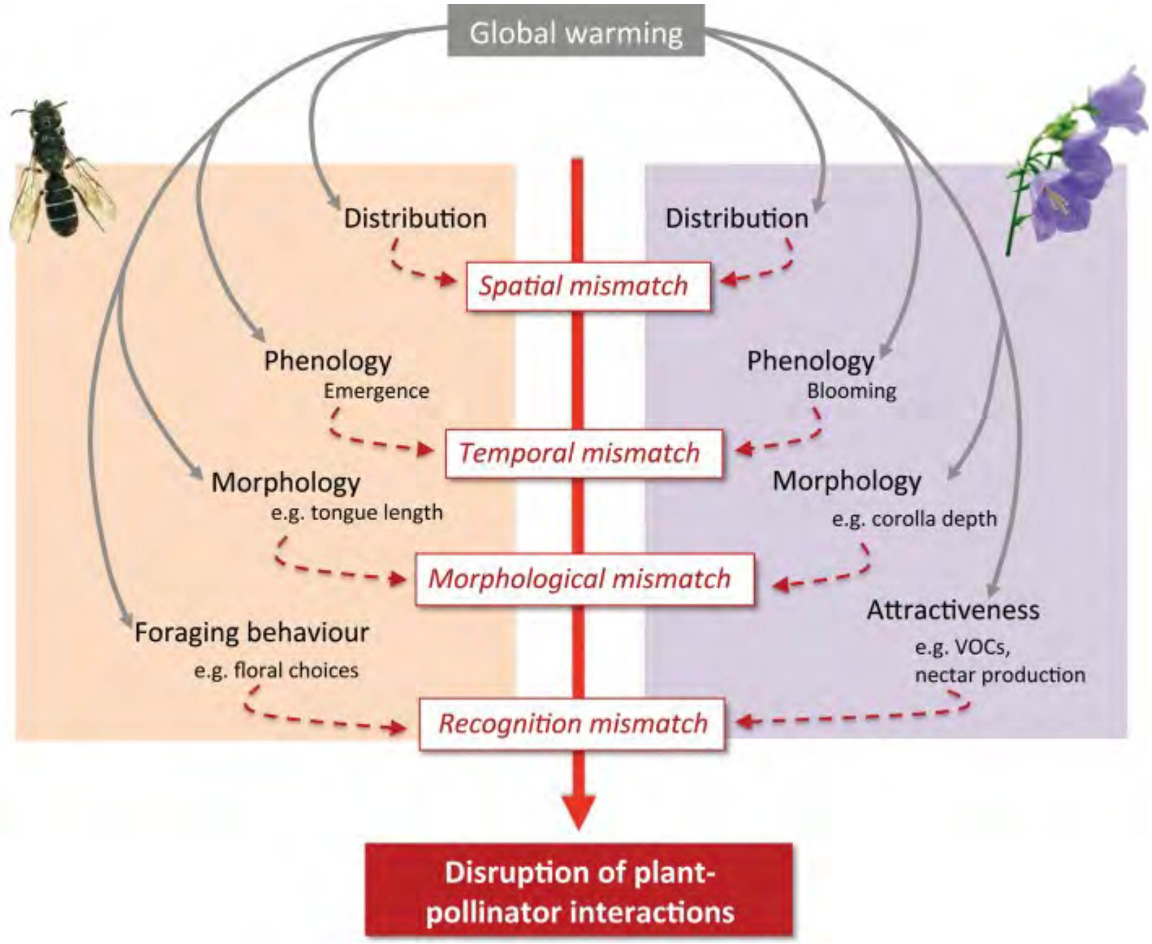


Figure 4-1: Phenological mismatch diagram (Gerard et al., 2020)

3.3.2 Forest Pests

While insects often provide beneficial ecosystem functions, there are of course examples of insects that are seen as destructive or detrimental to an ecosystem’s health. These are important to acknowledge so that forest managers can proactively develop plans and practices to address these problems.

Hemlock woolly adelgid (HWA) and spruce budworm are seen as forest pests by wildlife and forest managers, especially given the invasive nature of the hemlock woolly adelgid. They are particularly destructive in North America as they have no natural predators or checks to keep them from running rampant.

HWA is a forest pest that feeds solely on the sap of hemlock and spruce trees. Without the presence of predators, they are able to quickly expand and severely hamper the hemlock tree population. Not only that, but the HWA is also able to actively feed and develop during winter, which is not common for insects. This acts as a double-edged sword, as they are extremely susceptible to extreme weather events and winter temperatures. As such, overwintering mortality due to minimum winter temperatures is the main factor in determining HWA density and spread. Observations in Vermont indicate that average winter temperatures are warming 0.5°F per decade for the last three decades and that the number of very cold winter days (maximum temperature below 0°F) has been decreasing 3 days per decade since the 1990s (see Climate Change in Vermont chapter). These trends suggest winter survival of the HWA may increase along with increases in population growth rates towards northeastern edges of Eastern Hemlock trees (McAvoy et al., 2017).

Vermont is committed to studying the spread and distribution of invasive forest pests, with monitoring programs for a variety of the most common invasives and implementation of management strategies. Organizations such as Vermont Invasives provide valuable information to the public about aquatic and terrestrial invasive species while also giving community members the opportunity to participate through citizen science—contributing information and reporting sightings of invasives themselves.

3.4 BIRDS

3.4.1 Background

Birds represent a critical source of biodiversity in Vermont and provide a number of ecological functions that affect humans. Not only are birds a source of entertainment for birdwatchers, but as seed-dispersers and agents of natural pest control, they are vital to the ecosystem. When thinking about climate change impacts on birds, a critical issue is the impact it may have on phenological timing. This is especially true for migratory birds. Breeding migratory birds must have precise timing of their arrival to spring feeding grounds, as individuals arriving too early may be risking disadvantageous conditions or a constrained amount of food resources, while those arriving too late face difficulties in finding accessible mates or suitable breeding territories. To properly match their migration to environmental conditions, birds often synchronize their timing based on environmental cues like temperature and photoperiod. Figures 4-3 and 4-4 highlight this relationship, illustrating a tightly-knit association between arrival date of migrating birds and the trajectory of seasonal temperatures per year.

Researchers at the Vermont Center for Ecostudies have tracked an alarming trend of declining aerial insectivore bird species. They have noted a 2.5% annual decrease in bird counts in their study sites, equating to a 45% drop in their relative abundance over 25 years (Figure 4-2). With such a massive drop in abundance in a relatively diverse guild, it is likely that these declines represent broadscale changes—whether that be to insect phenology, pesticide use, or loss of insect habitats—and resultant declines in aerial insectivore abundance (Faccio et al. 2017).

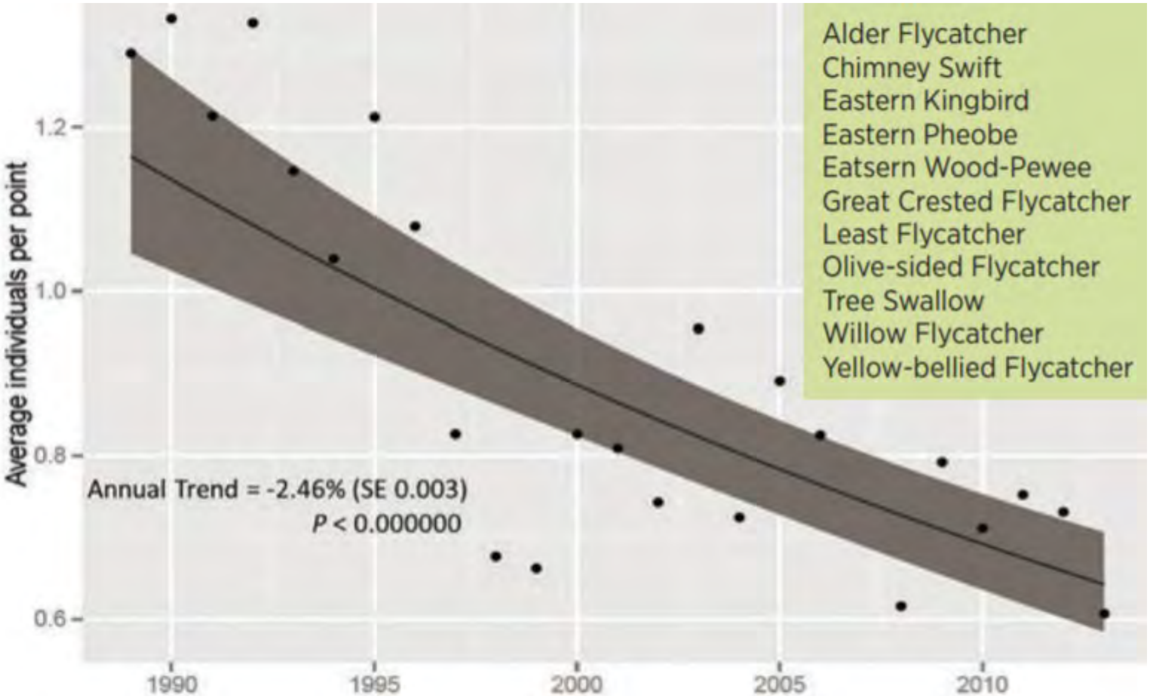


Figure 4-2: Aerial insectivore relative abundance per year measured in Vermont (Forest Bird Monitoring Project)

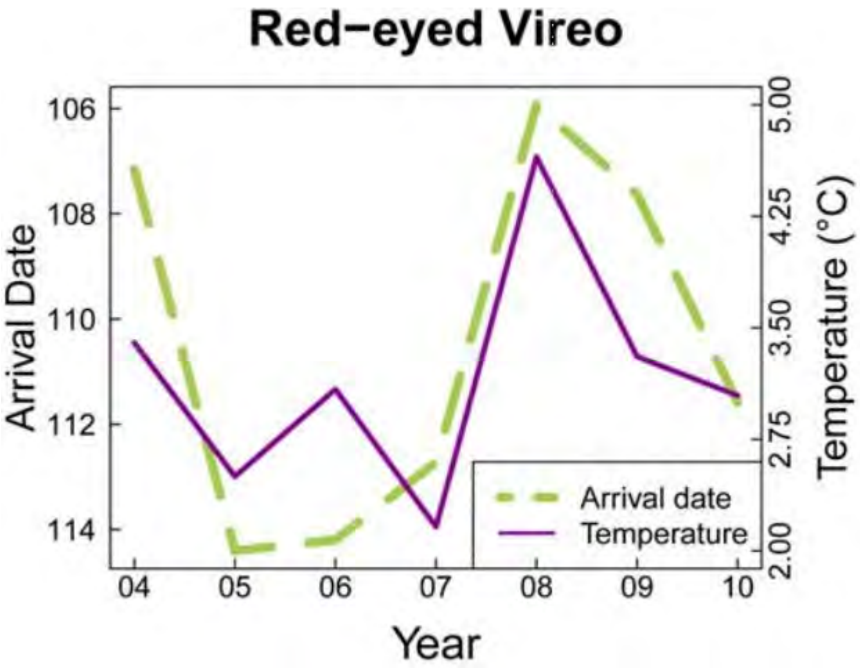


Figure 4-3: Phenological response and trajectory of temperature and arrival date for red-eyed vireo (Hurlbert doi:10.1371/journal.pone.0031662.g004)

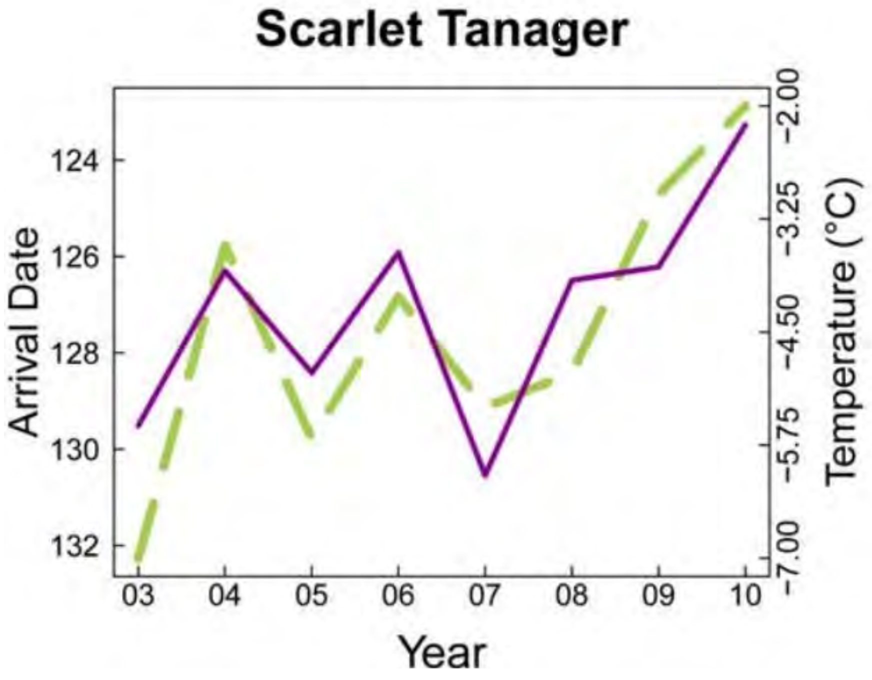


Figure 4-4: Phenological response and trajectory of temperature and arrival date for scarlet tanager (Hurlbert doi:10.1371/journal.pone.0031662.g004)

3.4.2 Seasonality

Increases in the average spring temperature in Vermont (+0.3°F since the 1990s) can have big impacts on plants. Changes in spring seasonality can jump-start the spring growing season, with a wide variability in how species have reacted to this change in timing in Vermont (Hurlbert and Liang, 2012). This variability can lead to phenological mismatch, where the phenological timings of interacting species shift at different rates. In migrating birds, this asynchrony can result in widespread starvation and decreased fitness of species if they migrate at a time when their food sources are either not available due to growth patterns, or have already emerged and were eaten by other bird consumers that had migrated at the correct time. Figures 4-3 and 4-4 highlight this pattern, illustrating how closely the arrival dates of different bird species coincide with the temperature, and how variable the timing can be.

Although many migratory songbirds are at risk of starvation and loss of breeding habitats due to warming temperature trends, there are cases of birds that could benefit from extended breeding seasons. Birds with the ability to lay multiple broods, such as the black-throated blue warbler, can sometimes utilize the extended breeding season for population growth and recruitment (Townsend et al, 2013). Yet nothing is straightforward—the black-throated blue warbler may be hindered by loss of hobblebush habitat that is maintained by browsing moose which are declining.

Vermont's winters are warming rapidly, with drastic changes to the structure of winter bird communities. As bird populations respond to warming climates through slow poleward migrations, overwintering bird communities are populated by increasing numbers of warm-adapted species across North America (Prince and Zuckerberg, 2015). This raises concerns of how this shift in community structure may impact the environment and landscape over time.

3.4.3 Habitats and Range Shifts

Researchers are observing a trend in poleward migrations of birds due to warming temperatures and landscape changes that could have drastic consequences for threatened species. In Vermont, the most well-known example is the Bicknell's thrush (*Catharus bicknelli*), a migratory bird with heavily restricted ranges that is one of the region's highest conservation priorities. As it only lives in mountainous habitats at high elevations with dense balsam firs, it is particularly vulnerable, and bioclimatic models predict over 50% of its suitable habitat will be lost by 2050 (Cadieux et al., 2019). Not only are warming climates pushing montane spruce forests towards extinction (see Climate Change in Forests chapter), but anthropogenic impacts such as ski areas, towers, and turbines have also resulted in habitat fragmentation in its regular breeding grounds (Hill and Lloyd, 2017).

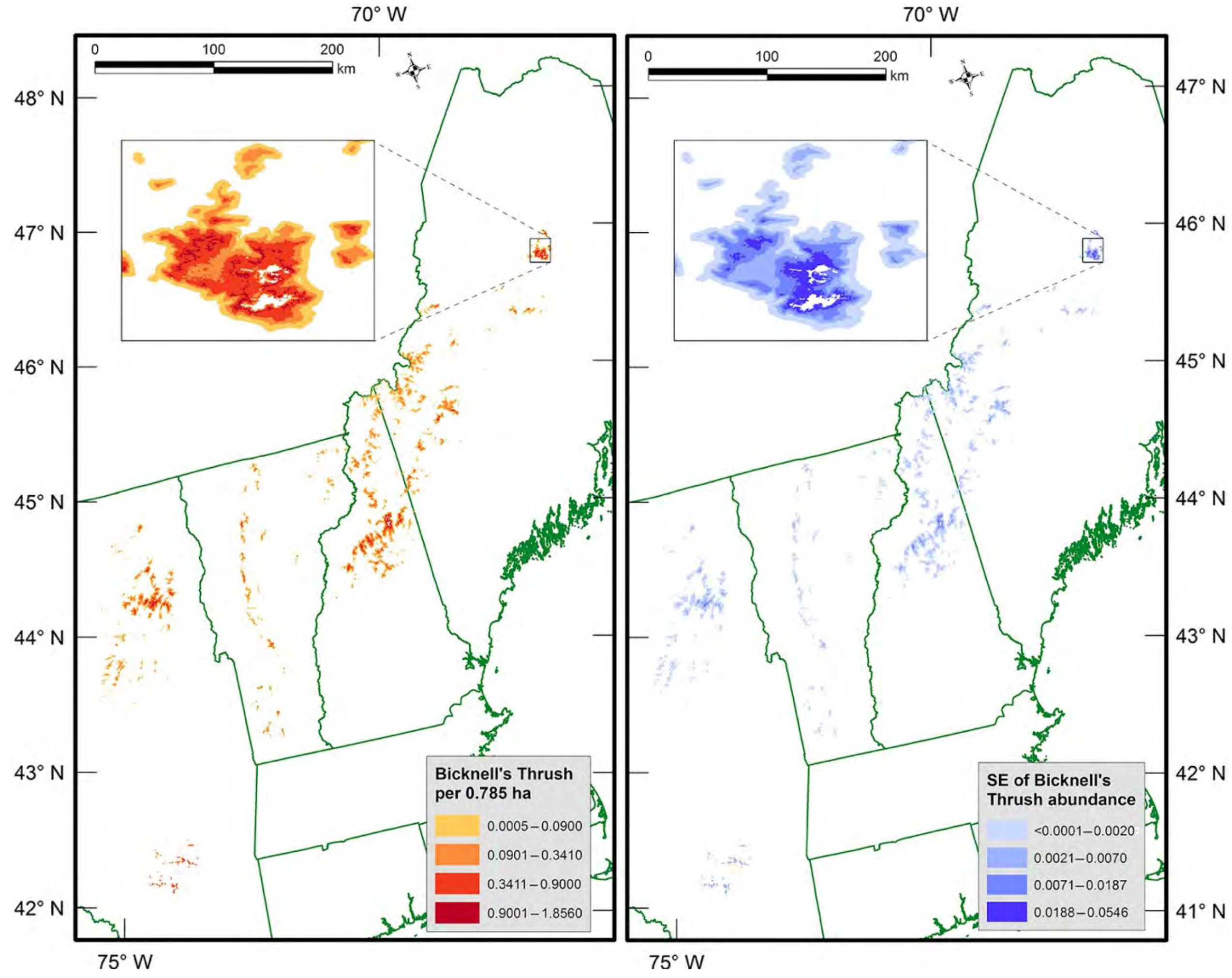


Figure 4-5. Estimated population density of Bicknell's thrush in 2016 (left panel) and its uncertainty (right panel). (Hill and Lloyd, 2017)

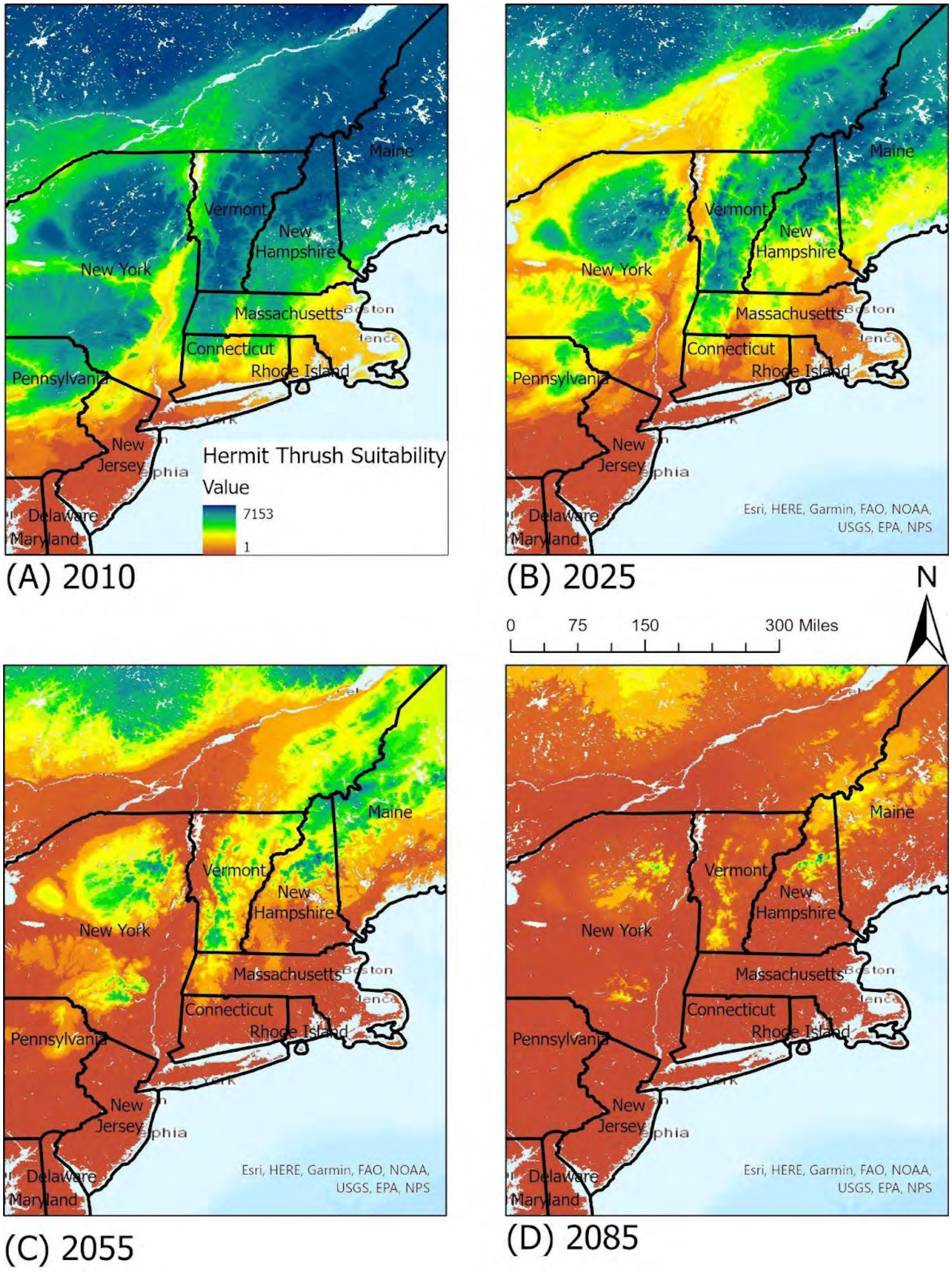
Wetland habitats are some of the best environments for water birds, as they provide shelter for breeding, nesting, and rearing of young, along with easy access to water and food. Many birds have adapted to these habitats and are reliant on the quality of the wetlands, such as the grebes. Vermont's primary wetland habitat is the Lake Champlain Basin, encompassing more than 300,000 acres of wetlands and home to a diverse population of waterfowl (USGS Wetlands as Bird Habitat). Wetland habitats for birds are being impacted by Harmful Algal Blooms and the effects of warming waters on freshwater plants and animals that birds depend on.

3.4.4 Notable Species in Vermont

The National Audubon Society conducted a comprehensive study of future range suitability for North American bird species. The full study can be accessed in an interactive online format via their Survival By Degrees website. For Vermont, under a Representative Concentration Pathway (RCP) 8.5 Climate Scenario with an overall increase of 3.0°C, 94 bird species were identified as moderately to highly vulnerable to climate change, resulting in loss of suitable habitat ranges. Here, we highlight four bird species because of their importance in Vermont and potential climate-related declines: hermit thrush, golden-winged warbler, common loon, American bittern, and pied-billed grebe.

Hermit Thrush

The state bird of Vermont, the hermit thrush (*Catharus guttatus*) is a small migratory bird that winters in the US. With a wide geographic range, current climate projections predict an overall 73 percent loss in current summer range by 2080, along with a large-scale shift northwards (Glennon et al., 2019). The hermit thrush's unique overwintering range makes it more vulnerable to shifts in winter seasonality.



(A) 2010

(B) 2025

(C) 2055

(D) 2085

Figure 4-6. Future suitability ranges of the hermit thrush under the RCP 8.5 climate scenario.

Note: High suitability values represent the areas most likely to sustain populations of that bird species. Sustainability ranges were developed through a combination of climate data and environmental data, including vegetation type, terrain ruggedness, and anthropogenic land-use. (Bateman et al., 2020)

Golden-Winged Warbler

The golden-winged warbler *(Vermivora chrysoptera*) is an interesting bird as an early successional species, requiring habitats with shrubs, sparse trees, and grass understories (see Climate Change in Forests chapter). As a result of increased human development and successive stages towards more forested areas, many of its ranges have been lost, and populations have dwindled. Currently, Vermont is the only New England state that hosts a population of golden-winged warblers (REF Audubon Center). Due to its specific habitat requirements, the golden-winged warbler can find some suitable habitats within Vermont at this point, but it is predicted that by 2055 much of the suitable ranges in the northeast will shift northwards (Figure 4-7).

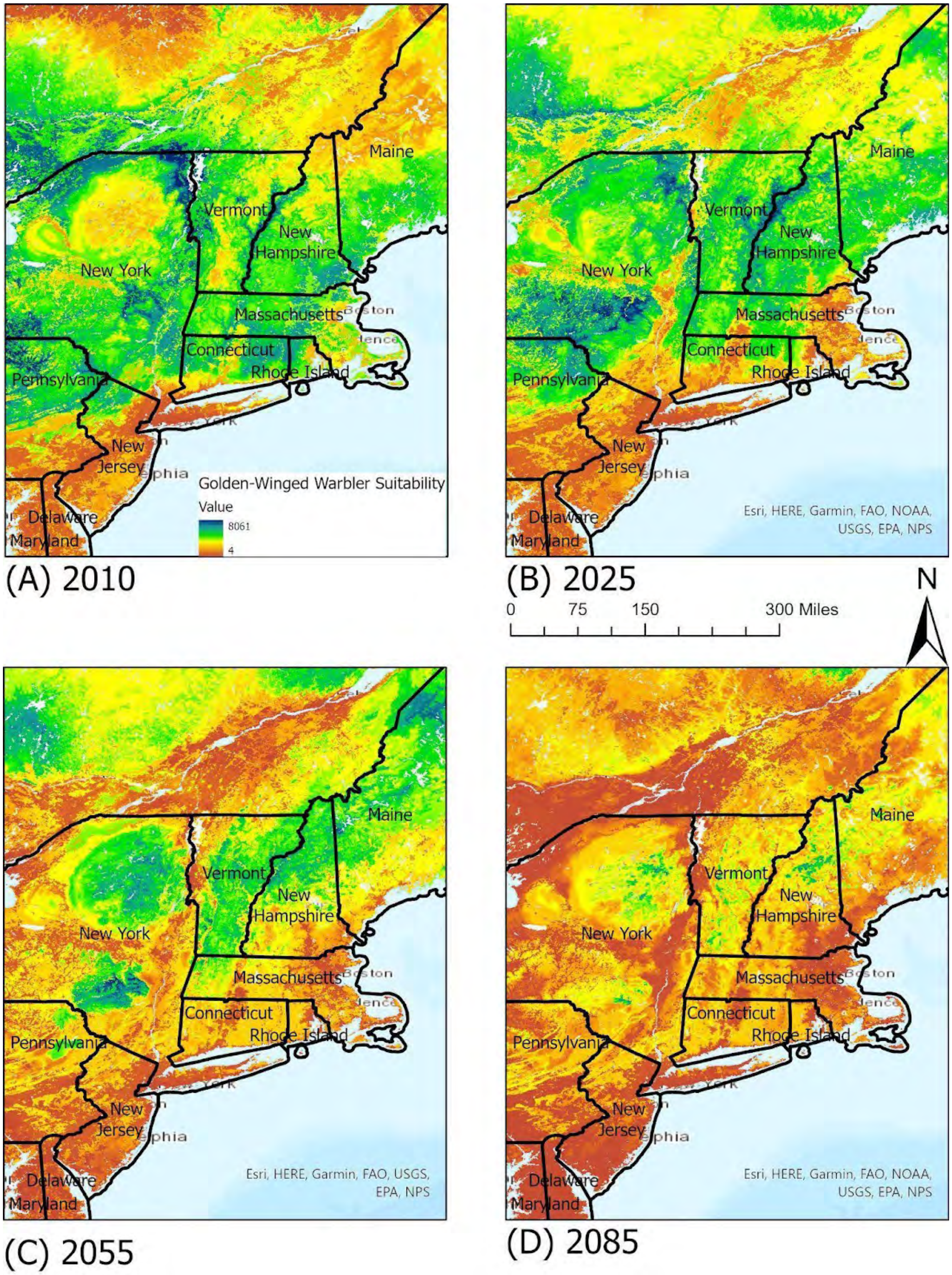
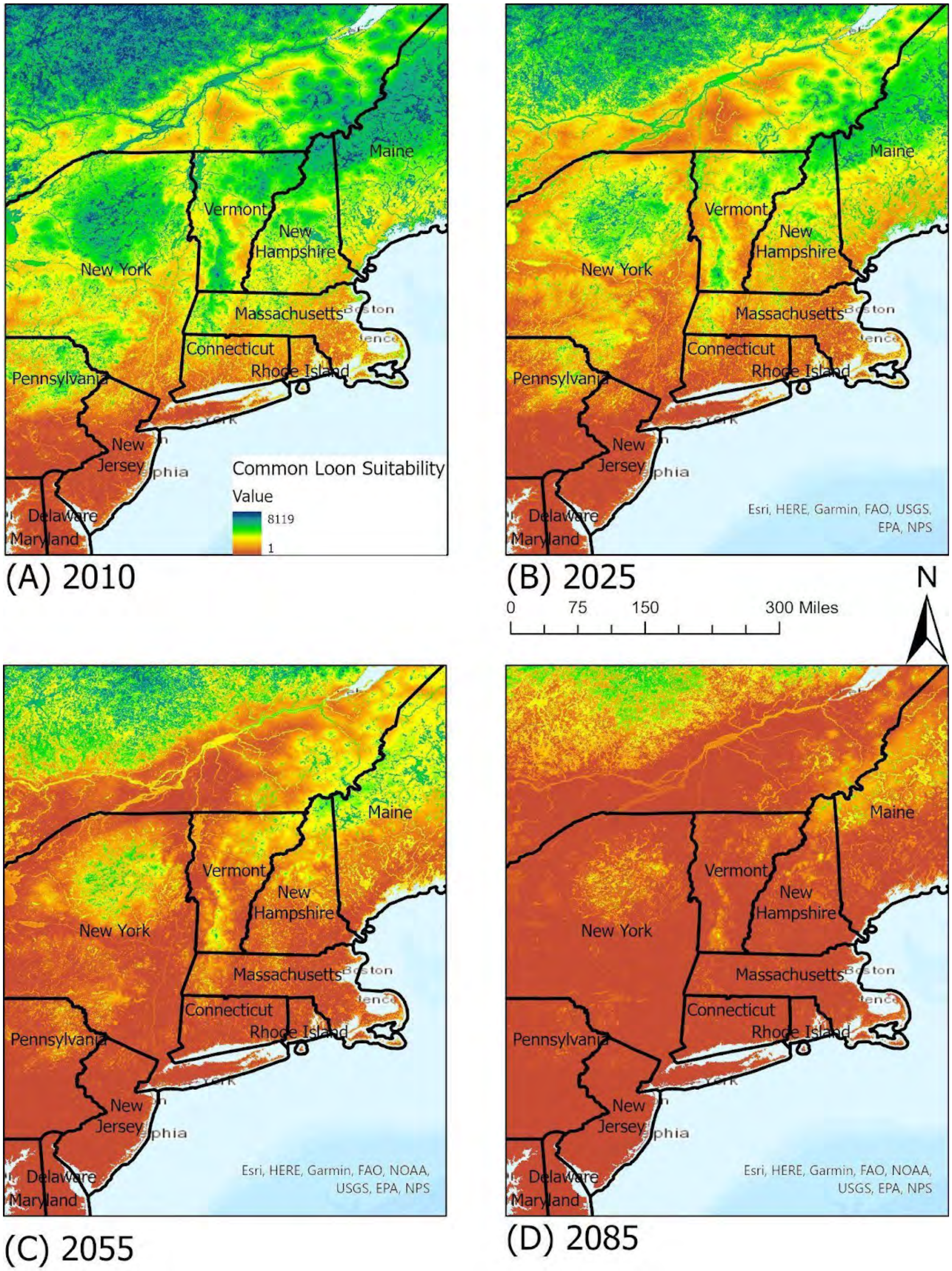


Figure 4-7. Future suitability ranges of the golden-winged warbler under the RCP 8.5 climate scenario.

Note: High suitability values represent the areas most likely to sustain populations of that bird species. Sustainability ranges were developed through a combination of climate data and environmental data, including vegetation type, terrain ruggedness, and anthropogenic land-use. (Bateman et al., 2020)

Common Loon

As one of four species of loon in North America, and the only breeding species in Vermont, the common loon (*Gavia immer*) is an iconic species in Vermont. It is often used as an indicator for lake health due to its reliance on available lake habitats and water levels. It shares much of its territory with humans, as nests will often be built along the shoreline of lakes and ponds during the nesting seasons, and so it is particularly susceptible to human interference and to water quality. Bianchini et al. (2020) found that anthropogenic effects on water bodies can have negative effects on reproductive success and population declines in the common loon, and cites acid rain and lake acidity as one of the key stressors. This demonstrates the intersectionality between wildlife and their environment, and highlights the importance of maintaining water quality and pH levels for wildlife health. Today, the common loon does have suitable ranges in Vermont's lakes and ponds, but under RCP 8.5 may have very few suitable areas by 2050 due to a combination of water quality and annual temperature changes.


(A) 2010

(B) 2025

(C) 2055

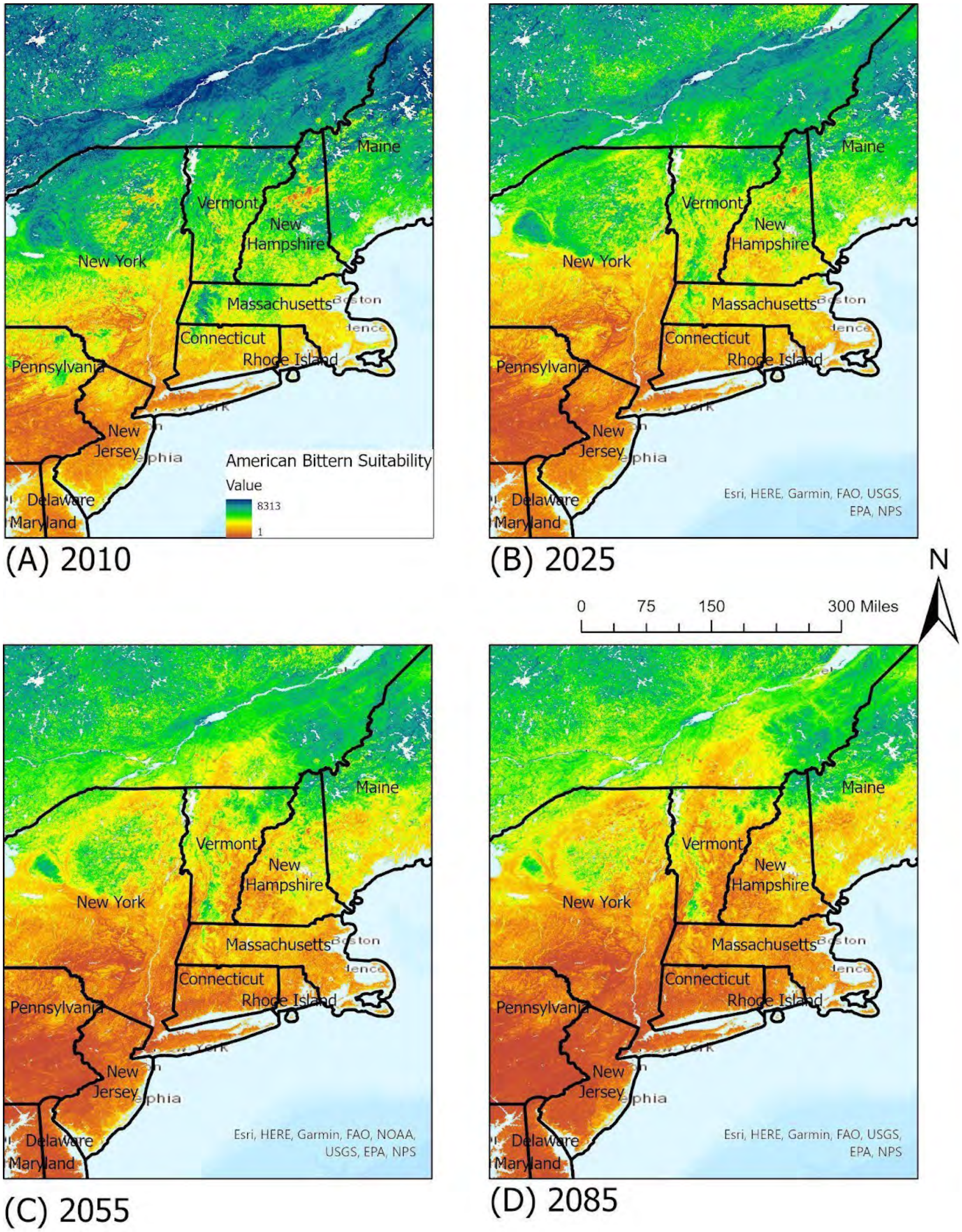
(D) 2085

Figure 4-8. Suitability Ranges of the common loon under the RCP 8.5 climate projections.

Note: High suitability values represent the areas most likely to sustain populations of that bird species. Sustainability ranges were developed through a combination of climate data and environmental data, including vegetation type, terrain ruggedness, and anthropogenic land-use. (Bateman et al., 2020)

American Bittern

A medium-sized, solitary heron, the American bittern is a common sight in freshwater marshes and wetlands, often hunting for fish and aquatic life in the shallow water. Its main nesting and foraging grounds are marshes and reedy lakes during both summer and winter, and occasionally it may feed in dry grass fields. On a national scale, the American bittern has experienced serious declines in the Southern portions of its breeding ranges, largely due to loss of available habitats and its reliance on large marshes. In Vermont, the American bittern has its suitable ranges located near water bodies such as lakes and ponds, much like the common loon. By 2085, under the RCP 8.5 scenario, its available ranges in the New England area will see an overall shift northwards as annual temperatures and seasonality shifts (Figure 4-9).



(A) 2010

(B) 2025

(C) 2055

(D) 2085

Figure 4-9. Suitability ranges of the American bittern under the RCP 8.5 climate projections.

Note: High suitability values represent the areas most likely to sustain populations of that bird species. Sustainability ranges were developed through a combination of climate data and environmental data, including vegetation type, terrain ruggedness, and anthropogenic land-use. (Bateman et al., 2020)

Pied-Billed Grebe

The pied-billed grebe is a common bird species found in temperate climates in North America in ponds, lakes, and marshes. Their diet consists of insects, fish, and other aquatic life. As they are reliant on water bodies and appropriate marsh habitats, pied-billed grebe in Vermont are most often seen around Lake Champlain and similar water bodies. Under the RCP 8.5 climate scenario, available suitable habitat for the pied-billed grebe is expected to decrease over time due to a variety of factors, including invasive aquatic plants and degradation of existing aquatic ecosystems. By 2085, they may be largely limited to lowland areas and the Champlain Valley of Vermont (Figure 4-10).

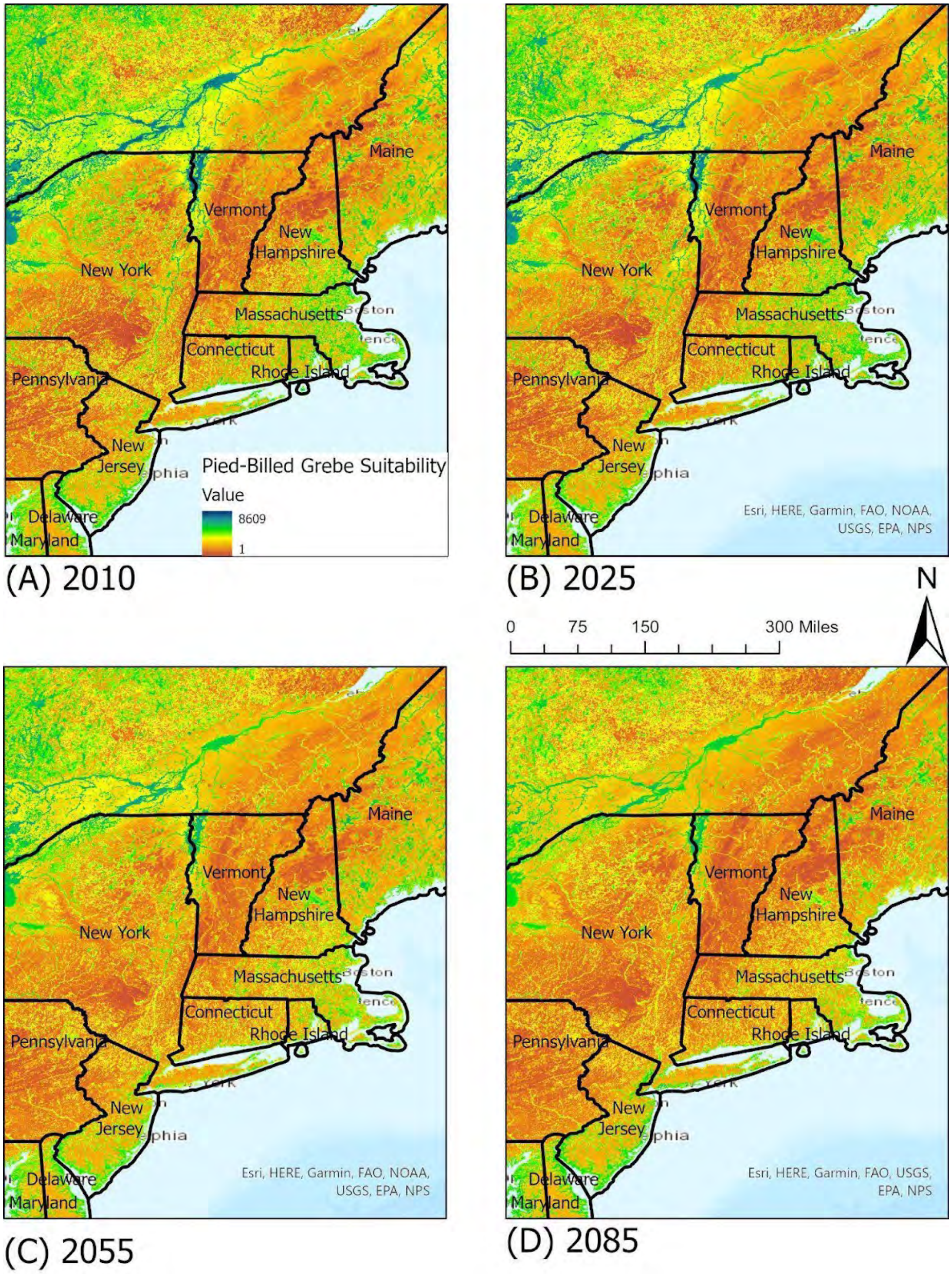


Figure 4-10. Suitability ranges of the pied-billed grebe under the RCP 8.5 climate projections.

Note: High suitability values represent the areas most likely to sustain populations of that bird species. Sustainability ranges were developed through a combination of climate data and environmental data, including vegetation type, terrain ruggedness, and anthropogenic land-use. (Bateman et al., 2020)

3.5 BATS

Like birds, many bat species are aerial insectivores and face similar challenges due to climate change. Vermont is currently home to 9 species of bats, with 3 of them being migratory tree bats that travel to the Southern US, Central America, and South America for winter. Like birds, phenological timing during migration and reproductive timing is critical to their success. There have been studies done across the United States that attempt to study climate and weather impacts on bat migrations (Luncan et al. 2013), which can provide insight as to their conditions in Vermont. Studies done on the Indiana bat (*Myotis sodalis*) have found that warming temperatures have had a prominent effect on habitat suitability, and increased warming may lead to potential range shifts and large-scale movement patterns northward, with the potential of new bat species roosting in Vermont (Loeb and Winters, 2012).

The main issue that bats face in Vermont at this point in time is the fallout from the arrival of white-nose syndrome in 2006, which has resulted in the loss of more than 5.7 million bats in the Northeastern United States. The two most common species in Vermont, the little brown bat (*Myotis lucifugus*) and the northern-long-eared bat (*Myotis septentrionalis*), have seen a 90% decline in population. Commonly contracted due to exposure to a fungus inside bat hibernacula (*Pseudogymnoacscus destructans*), this disease results in attacks on the bare skin of hibernating bats and can cause abnormal behavior that can result in early mortality. With such drastic declines, Vermont is losing out on a number of critical services supplied by bats, and an important component of the food web is also missing.

It is uncertain how the impacts of climate change will interact with that of climate change. While microclimate conditions have been shown to affect the growth of the fungus, it is difficult to predict how climate change and the white-nose syndrome epidemic will interact on a large scale. Further research is required to understand the effect that rises in temperature and variation in cave microclimate(humidity) will have on bat infection rates and mortality (Maher et al, 2012).

Figure 4-11. White-nose syndrome in bats has resulted in the loss of 5.7 million bats in the US

Bats provide critical ecosystem services like pollination, fruit dispersal, and arthropod control. Due to their sensitivity to environmental stressors, they can also serve as ecological indicators of habitat quality. With insectivorous bats occupying high trophic levels, monitoring of their populations and health would allow researchers to identify contaminants or environmental disturbances very easily. Dietary accumulation increases as you go up the food chain, therefore bats would likely be able to show the consequences of pollutants in the environment much sooner than herbivorous insects or birds (Jones et al., 2013). To prevent disease outbreaks like white-nose syndrome from occurring, wildlife managers and researchers should be encouraged to collect baseline population data for a variety of species, not just bats, so that negative stressors and impacts in a population can be quickly discovered and investigated.

3.6 LARGE UNGULATES (MOOSE AND DEER)

Though moose (*Alces alces*) and white-tailed deer (*Odocoileus Virginianus*) are both large ungulates, their responses to climate change serve as direct points of contrast rather than comparison. Moose are generally anticipated to become physiologically stressed in response to warming temperature trends and deer have clear survival advantages due to the warmer temperature and decreased snowpack. So, while not in direct competition, their population trends do follow opposing directions in response to warming climate patterns.

White-tailed deer distribution and abundance are heavily affected by winter severity, which is often measured by two variables, ambient temperature and snow depth (high confidence). Winter snow depth can affect body conditions of deer and increase movement costs, primarily affecting maternal body condition and reducing future reproductive success. Deer are often reported to have a thermal tolerance close to 19.4°F (-7°C), below which begins the potential for physiological and behavioral responses. Average annual winter temperatures are trending to be greater than this thermal tolerance and extremes are changing—extremely cold days (max. temperature <0°F) are decreasing and warm winter days (>50°F) are increasing (see Climate Change in Vermont chapter). More variation within the winter season could bring unexpected physiological or behavior changes (e.g., shedding, foraging). Snow depth affects deer but can be a problematic measurement, as snow drifts skew measurements at particular locations or times and can lead to inconsistencies. Snowfall, while not a perfect proxy for snow depth, is a more accurate measure of snow, and has been decreasing for the last 60 years in Vermont (see Climate Change in Vermont chapter) but is greater than when measurements began in the 1930s. As such, the near-term outlook is that snow, and therefore snow depth, may not change substantially in the coming decades but could be seriously reduced beyond 50 years in the future. These winter conditions can directly affect deer populations through survival effects, as well as indirectly by impacting reproduction and fecundity of females (Weiskopf et al., 2019)

Substantial evidence has been collected to indicate that increasing temperature conditions and decreased winter severity leads to increased abundance of white-tailed deer; changes in migratory behavior; altered foraging, habitat selection, or behavior; and a potential increase in hemorrhagic disease outbreaks (Weiskopf et al., 2019). There are complexities to this situation that should be considered. One example is the potential loss of hemlock trees, an important thermal shelter for deer, due to warming winters and the invasion of the HWA. These changes to forest composition could result in near-term difficulties for deer during this shifting temperature regime (McClure, 1990).

Range shifts in deer may occur due to warming temperatures and as a result of climate-induced habitat changes in the northern U.S. For example, oak species (*Quercus* spp.) are predicted to increase in both range and abundance in some areas of Northern Wisconsin and Upper Michigan, providing increased mast production that serves as high-energy food sources for deer. This could encourage a steady shift in deer population northwards into previously unsuitable habitats; however, deer can also browse oak heavily enough to limit the survival of regenerating stands. There may be a cyclical dynamic between deer and oak abundance as oak species try to shift northward.

In Vermont, hunting has always been a major component of human interaction with the landscape. Annual harvests are tracked by the Vermont Fish and Wildlife Department. Deer harvests across Vermont have been steadily increasing in the more northern region of Vermont in the past few decades (Figure 4-11), although this could reflect either a change in population or in hunter effort. Figures 4-12 and 4-13 represent mean deer harvests by town per decade in a southern and northern county, respectively, illustrating an overarching pattern where deer harvests are observed in increasing numbers northwards over time. Wildlife managers should take these shifts into account when developing landscape management plans, as well as the predicted boom in deer population as ambient winter temperature increases per year. Increased hunting interest or success rates and higher bag limits are major reasons for these observed spikes in harvest, which serve an important role in controlling the population of deer and moose.

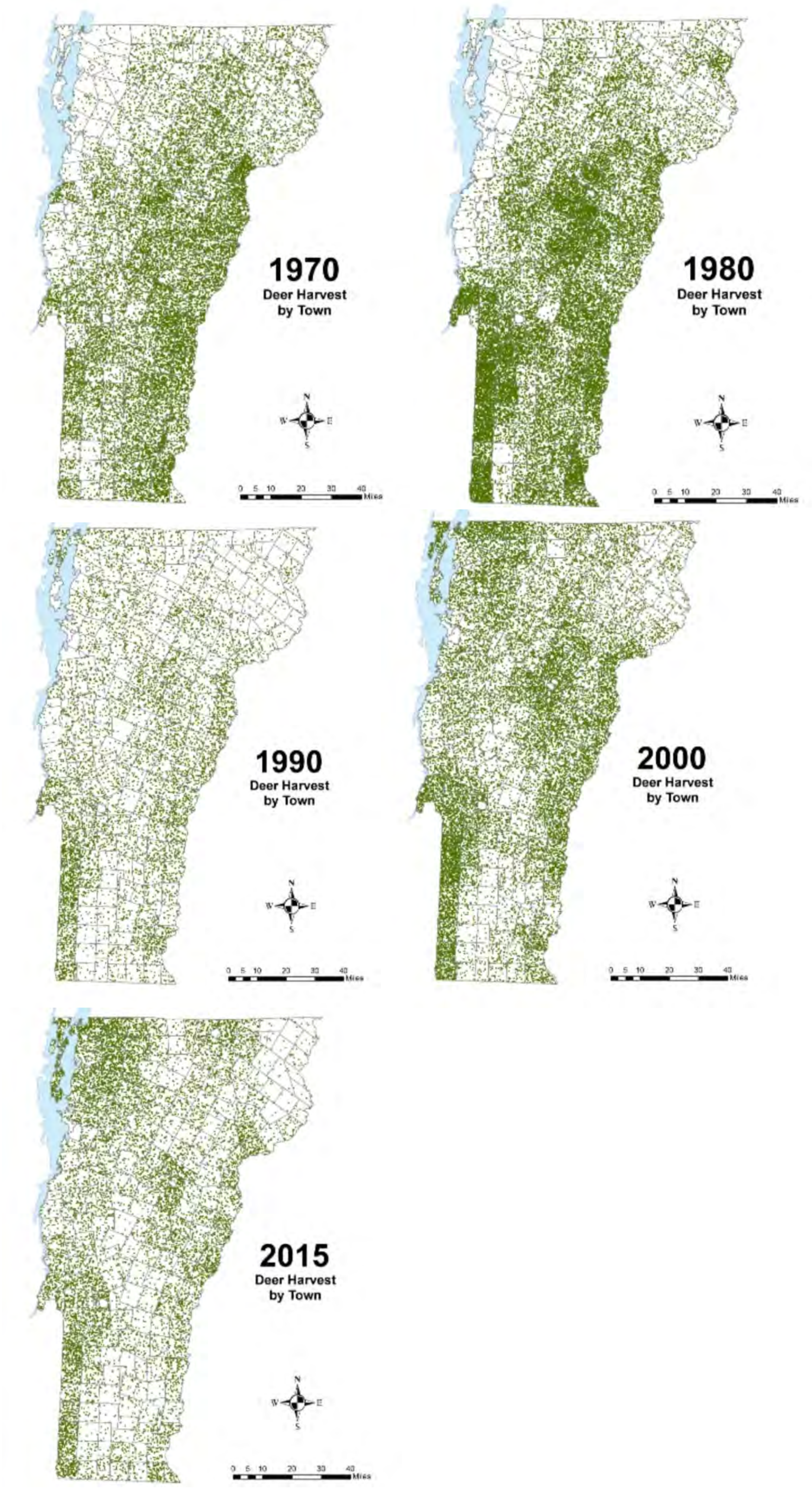


Figure 4-12. Annual deer harvests by towns in Vermont from 1970-2015. (VT Fish and Wildlife Department, 2020).

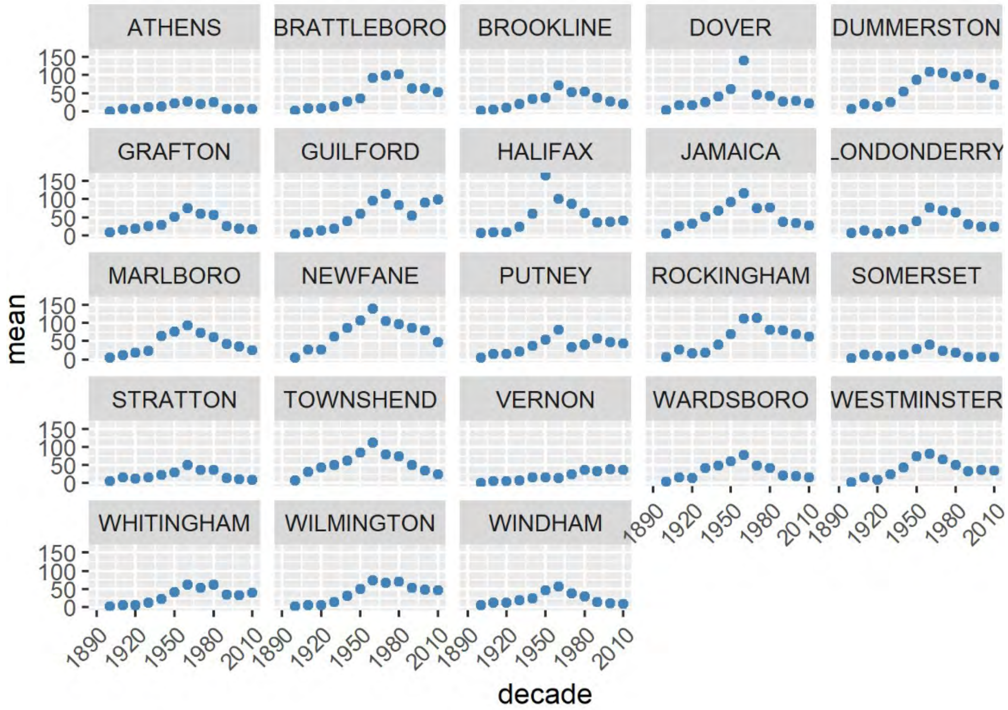


Figure 4-13. Mean deer harvests by town per decade in southern VT's Windham County (VT Fish and Wildlife Department, 2020).

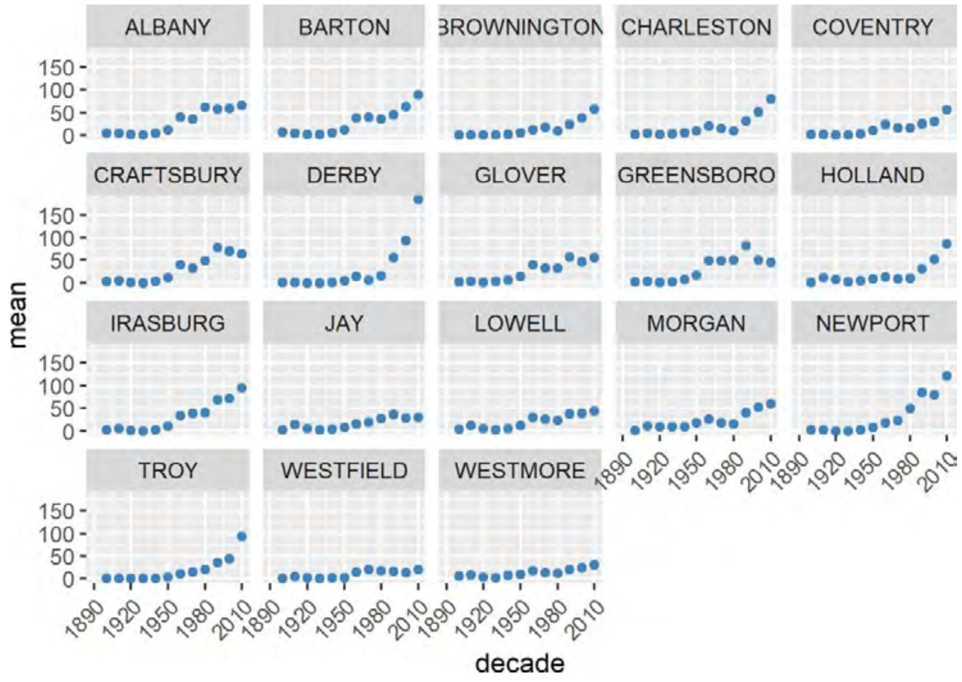


Figure 4-14. Mean deer harvests by town per decade in northern VT's Orleans County (VT Fish and Wildlife Department, 2020).

CASE STUDY: DEER HUNTING AS A SOCIAL-ECOLOGICAL CLIMATE CHALLENGE

Objective & Approach

Deer hunting may be the most recognizable expression of Vermont's hunting culture (Boglioli, 2009), making it a useful case to investigate possible ecological and social impacts of climate change on hunting in the Green Mountain State. This subsection uses a nexus approach, which is helpful for looking at data and trends from many fields (Liu et al., 2018). Here, we examine the outlook for deer hunting in Vermont under climate change through the lenses of wildlife population health and social demand, supported by links to three other chapters of the Vermont Climate Assessment. This analysis integrates a high-confidence ecological assessment with two less-certain social scenarios to highlight risks and opportunities for wildlife management.

Box 1: Key Messages

Ecological conditions under climate change will favor increased deer populations in Vermont causing undesirable damages to forests (high confidence), but the social prognosis for hunting as a culturally important practice for recreation, food, and deer management is uncertain (medium confidence).

Ecological and Social Assessments

Accounting for climate change, the ecological prognosis in Vermont for white-tailed deer, a widely-sought game species, is promising (VT Fish and Wildlife Department 2020). Vermont's deer population is broadly healthy, with substantial local variation that requires active management to balance. Even-aged forests provide limited habitat in the more remote portions of the state and support fewer deer than historical precedent, while some agricultural areas attract an overabundance of deer resulting in competition that reduces individual fitness and leads to overbrowse in regenerating forests (VT Fish and Wildlife Department 2020). In the coming centuries, forest community structure is likely to shift towards transitional hardwood species like red oak and shagbark hickory (see Climate Change in Forests chapter), providing more abundant forage for deer (Rodenhouse et al., 2009; Blossey et al., 2019). Shorter term changes in forest structure, such as the continued decline of eastern hemlock by the end of the century (see Climate Change in Forests chapter), may introduce stress if not immediately congruent with decreased winter intensity, but may also result in increased early successional habitat that favors deer (Fortin, personal communication, 2021). Potential urban and peri-urban development (see Community Development chapter) is unlikely to pose a threat to the species, which is relatively tolerant of development (Gaughan and Destefano, 2005).

Anticipating that deer populations in Vermont will grow in the coming decades, the ecological need for increased deer harvest to maintain healthy population sizes, limit overbrowse of regenerating forests, and minimize human-deer conflict will also likely rise (Fish and Wildlife, 2020). It is less certain if the social demand for hunting will match the ecological need for harvest. Key to this balance are several concurrent factors that, while not directly linked to climate change, may affect the social demand, or tolerance, for deer hunting in Vermont. Nationally, an aging participant base, urbanization, and changing wildlife values are associated with declining per-capita hunter participation since the mid twentieth century (Manfredo et al., 2020; Winkler and Warnke, 2013). Vermont exhibits each of these trends, albeit with anecdotal evidence of less severe declines in demand for, and tolerance of, hunting. Hunting license sales have fallen from over 100,000 in the early 1980s to just over 50,000 in 2016. However, sales increased during the pandemic—even controlling for new data collected by the state on multi-year license holders (Figure 4-14). Likewise, while a plurality of Vermonters hold “mutualist” wildlife values not commonly associated with support for hunting (Figure 4-15 for trend and definition), public support for deer hunting in Vermont remains high (VT Fish and Wildlife Department, 2020; Boglioli, 2009).

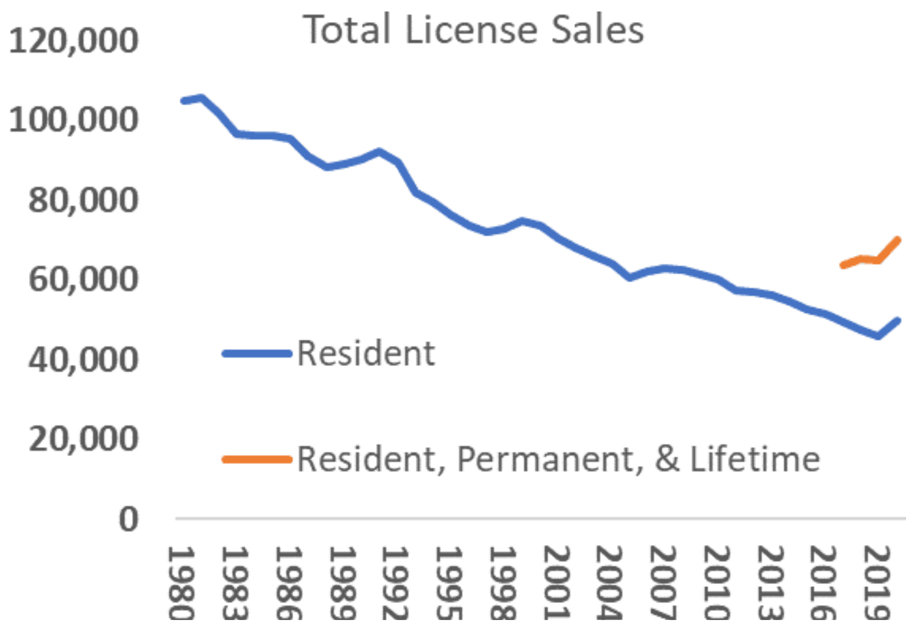


Figure 4-15: Sales of resident hunting and combined fishing-hunting licenses. Note: Records for people using lifetime and permanent licenses have only been available since 2017 (VT Fish and Wildlife Department, 2021b)

Urbanization also affects hunter participation. Urban and suburban development may increase due to Vermont's recent trends in parcelization (Fidel and McCarthy, 2018), and desirability to non-residents for second homes and outdoor amenities (See Community Development). Changing demographics and land uses could fuel further value change in the Vermont population. Well-established research on wildlife values suggests that urbanization correlates with value shifts away from the "traditionalist" values held by a plurality of Vermont hunters (Dietsch et al., 2018; Manfredo et al., 2020). However, measures of public values and attitudes around wildlife that represent more diverse traditions than those shown in Figure 4-16 are gaining traction in research and practice (e.g. Himes and Muraca, 2018). Future wildlife management in Vermont that recognizes diverse values and attitudes will be especially important for honoring the longstanding wildlife practices—including deer hunting—of the Abenaki (Wiseman, 2001 p. 42-43; 56). In addition, alongside increased land development, there is a current trend of decreasing public access to private lands, rigorously documented in Eastern states (Jagnow et al., 2006; Snyder et al., 2008; Walberg et al., 2018) but only anecdotally described in Vermont to date. Increased limits on public access to private land would further challenge hunting and other outdoor pursuits (see Recreation and Tourism chapter). In a worst-case scenario, hunter decline and decreased land access, driven by social value change and shifting land-ownership patterns and norms, would result in hunting becoming a less effective approach to balancing Vermont's growing deer population—creating a social and ecological challenge for wildlife managers.

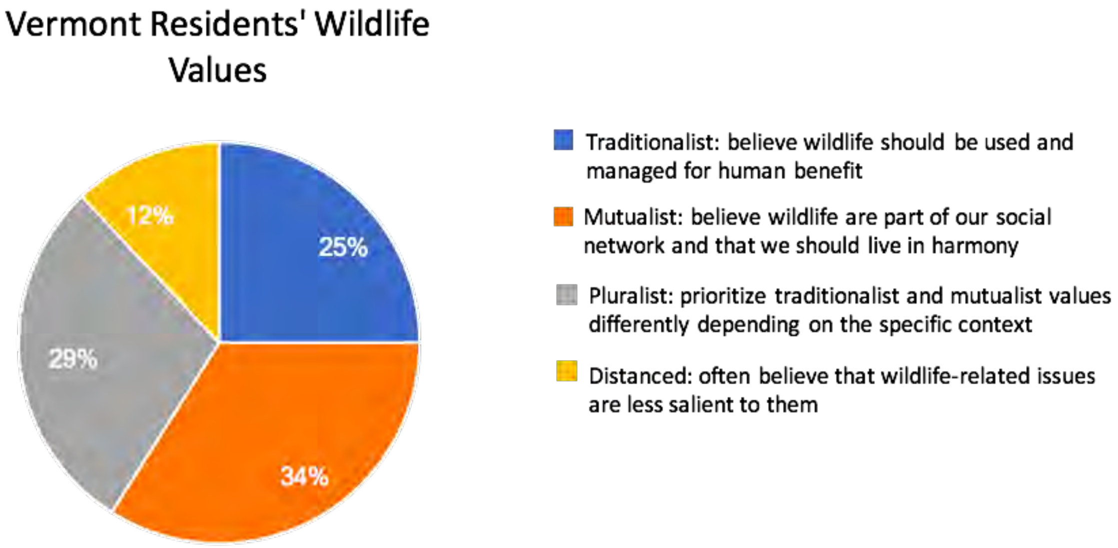


Figure 4-16: Vermonters' wildlife values based on a representative survey of 678 respondents. (Dietsch et al., 2018)

Alternatively, recent trends suggest a different plausible future scenario rooted in the widely-documented potential of major social and ecological upheavals to reshape human relationships with the environment and natural resources (Marshall et al., 2005; Tidball, 2012). The COVID-19 pandemic drove an increase in hunting participation, as both license sales and enrollment in hunter education courses (now available online) exceeded benchmarks from recent years (Figure 4-14; Meier, personal communication, 2021). Recent research into the pandemic's impacts on outdoor activities and values from nature confirms these recent trends, suggesting that Vermonters are relying on nature to cope with crises (Morse et al., 2020)—and that the pandemic may have created new opportunities for outdoor experiences like hunting (see Box 1). While the pandemic is an imperfect proxy for the sustained social changes brought by climate change, it does illustrate the possibility of resurgent social demand for hunting, consistent with the literature of nature engagement in response to upheaval (Tidball, 2012). Maintaining this momentum as the pandemic recedes, and nurturing it in the face of future upheavals, will require a multi-pronged effort tapping into both traditional and emerging veins of public support for, and interest in, hunting. The Vermont Land Trust's efforts to include access for hunting on conservation easements and Vermont Fish and Wildlife's "Wild Kitchen" programming, which connects diverse hunting and locavore communities, are examples of two such initiatives (VT Fish and Wildlife Department, 2021a; Slayton, 2019). Emerging research suggests pathways to augment this work. Future efforts could engage with rapidly emerging affinity groups in the hunting community—through organizations like Hunters of Color, Artemis Sportswomen, and Backcountry Hunters and Anglers—and university students to connect new hunters with land and resources and could continue to tie into Vermont's strong local food ethic to appeal to these stakeholders (Vayer et al., 2021). With proactive engagement, a best-case scenario could match a growing deer population with sustained or increased social demand for hunting.

Box 2: New Hunters, the Pandemic, and Cultural Relevance

"I grew up accompanying my dad hunting occasionally, but lost that connection when he died when I was twenty. I have been interested for a number of years, especially thinking about connection to land and the animals we eat, but felt there were just enough barriers to keep me from getting (re)started. This past fall was when I first started hunting in earnest. Thinking about it, a number of things coincided at the right time to make it possible for me to get over the hump. Crossbows being allowed for all hunters, hunters safety courses being online, having access to land, having lots of time because of the pandemic, and having friends to help me get through the myriad questions one needs answered to just get started. Certainly, I don't think I would be hunting if not for the pandemic. I ended up spending a good part of last year in a rural place and with lots of

time on my hands, and so was able to give foraging, fishing, and hunting the many hundreds of hours needed to start. During deer season in October and November, I felt I was able to catch up on the many hours of 'five years hunting with a dad' that some hunters are lucky to receive."

-Kristian Brevik (33), Burlington Vermont

Synthesis

This case study finds potential to meet the ecological challenge of an expanding deer herd under climate change with increased hunter participation. However, this best case outcome is not set in stone. Active effort will likely be required to support and sustain any new social demand for hunting that arises in response to future crises. Absent a proactive approach to both the ecological challenges facing—and social dimension affecting—Vermont's deer herd and hunting culture, a misalignment between deer population and social demand for hunting could occur if value change and shifting patterns of land ownership and access are exacerbated by climate change. With this in mind, sustaining deer hunting in Vermont during an era of climate change will require collaborative engagement from ecologists, social scientists, community planners, and a wide variety of stakeholders.

3.7 AQUATIC SPECIES

As global mean temperature continues to increase annually, subsequent warming of water bodies will also have a profound impact on the ecosystem. As aquatic species are exposed to new thermal habitats, community structures and trait distributions may see radical reshuffling as organisms respond to warming climates.

3.7.1 Riverine and Stream Ecosystems

Warming climate trends will have a variety of effects on physical aspects of riverine systems, with major consequences to organisms living in the system (Ficke et al., 2007). Increased water temperature reduces the amount of available oxygen in the system, potentially leading to the creation of hypoxic/anoxic zones where there is very little oxygen in the water, often causing health issues and mortality in aquatic species living there. Common fish species such as trout and salmon, and warm-water fish like smallmouth bass rely on groundwater discharges for cooler refuges during summer seasons. These refugia will decrease in availability as groundwater temperature is expected to increase over time (Ficke et al., 2007). Rivers will also see changes to the timing and amount of precipitation seen throughout the year. Warming temperatures will likely lead to reduced snowpack—decreasing spring flows and negatively affecting fish species. Increased temperature may also lead to increased toxicity of pollutants in the system, as common pollutants such as heavy metals and organophosphates become more toxic with rising temperatures.

Within riverine systems, many species of freshwater fish are expected to migrate due to shifts in water temperature. These migrations will result in compositional shifts and loss of ecosystem services, as freshwater fish communities shift from cold-water species to more warm-water species. Fluctuations in ambient water temperature may also result in shifts in seasonal flow and potential changes to growth rates of aquatic species (Xu et al., 2010). Biswas et al. found that freshwater lake communities in Ontario, Canada, are predicted to see an increase in species richness of 60-81% due to this migration, but a subsequent decline in functional diversity. Jones et al. also made similar predictions, finding that in the US on a national level, current climate projections and increased air temperature will lead to increased water temperature, rendering some fish habitats unsuitable for native species. As cold-water fish species such as trout are more susceptible to changes in thermal habitats, the loss of available cold-water fish habitats may result in considerable economic loss. This would have dramatic impacts on the present distribution of sport and commercially valuable fish and cause considerable losses in commercial and recreational fisheries.

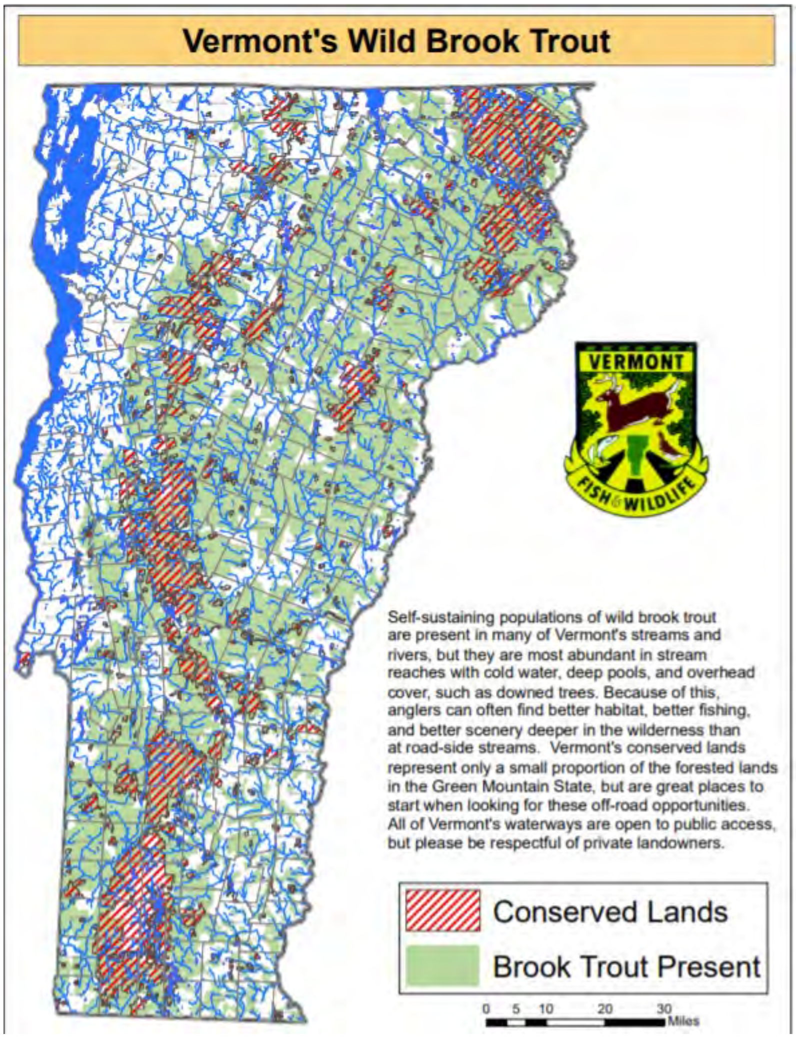
Fish Passage and Ecological Connectivity

Similar to terrestrial animals, fish are heavily reliant on their physical landscape and connectivity in order to migrate, move through different environments at different life stages, and take advantage of multiple habitat types. Habitat fragmentation is a key issue that has widespread impacts on fish, such as salmonids like the Eastern brook trout, and overall aquatic diversity (Hudy et al., 2008). Infrastructure such as roads and dams have severely hampered the mobility of aquatic species, and current road-stream crossing designs have proven ineffective in most cases. Heller (2007) has demonstrated that in many water bodies of the US, over half to two thirds of current road-stream crossings serve as a form of barrier for fish migrating and for fish seeking cold refugia during hot spells. During flooding and storm events, road-stream crossings and culverts are particularly susceptible to damming as the floodwater may exceed capacity and clog it with debris and sediment. Climate change is already affecting not only water temperatures but also frequency of abnormal weather events such as heavy rainfall events (see Climate Change in Vermont chapter) and increased stream-flows (see Water Resources chapter). As Vermont's annual precipitation has been increasing by 7.5 inches since the 1900s, precipitation across all seasons is expected to increase and put strain on the infrastructure, creating more issues for wildlife expected to utilize them (see Climate Change in Vermont chapter).

Brook Trout

Brook trout (*Salvelinus fontinalis*), Vermont's state fish, are an important component of Vermont's aquatic fisheries—they make up a large portion of Vermont's cold-water fishery resources, along with brown and rainbow trout. Together these three species are the most popular fish for open water anglers (Responsive Management 2021); although Vermont anglers have reported less time is spent on brook trout fishing than in previous decades, declining from 79% of anglers in 1990, to 67% in 2010 and a statistically significant decrease to 58% in 2020 (Responsive Management 2021).

Brook trout provide a clear example of how climate change may affect aquatic species as a whole. Like many other fish, they are known to be stenothermal, and are unable to tolerate anything beyond a small range of temperatures. As such, they require cold streams (often below 20°C) for their optimal habitat. Due to global temperature increases, brook trout are expected to experience range contractions, severely limiting their ability to reproduce and inhabit stream ecosystems. Based on current warming scenarios, a warming of 3.8°C is predicted to result in a reduction of 89% to thermally-suitable habitats for brook trout in North Carolina and other Southeastern portions of North America. In Southern Ontario, Canada, a study of two headwater streams found that a 4.1°C increase in summer air temperature could reduce thermally suitable habitats by 42% and 30% respectively (Meisner, 1990).



Self-sustaining populations of wild brook trout are present in many of Vermont's streams and rivers, but they are most abundant in stream reaches with cold water, deep pools, and overhead cover, such as downed trees. Because of this, anglers can often find better habitat, better fishing, and better scenery deeper in the wilderness than at road-side streams. Vermont's conserved lands represent only a small proportion of the forested lands in the Green Mountain State, but are great places to start when looking for these off-road opportunities. All of Vermont's waterways are open to public access, but please be respectful of private landowners.

Figure 4-17. Current distribution of Vermont's wild brook trout and conserved lands/waterways. *Wilderness Brook Trout.* (n.d.). VT Fish and Wildlife Department. Retrieved July 29, 2021, from https://vtfishandwildlife.com/wilderness-brook-trout

3.7.2 Lake Systems

Climate Change impacts on algal blooms (HABs)

Lake ecosystems are an attractive environment for both humans and wildlife, with many of Vermont's lakes serving important biological functions for nesting birds and aquatic species that live there, as well as offering recreational and economic benefits for humans. The projected changes to water and air temperature raise concerns about the general health of the lake ecosystem and possible consequences that wildlife and landscape managers should be aware of.

One of the main climate change concerns is eutrophication and the health of water bodies in Vermont. Eutrophication is the process where water bodies become heavily enriched with nutrients (e.g., nitrogen, phosphorus) that feed plant and algae material in the water. The nutrients typically come from human activities, such as excess urban and agricultural runoff. The enrichment of nutrients causes increased macrophyte and algal growth. Increases in macrophytes can stimulate algal blooms that lay on the water surface, blocking sunlight and limiting the growth potential of underwater plants while also being a nuisance for many lake-goers. Once these algal blooms die, they are decomposed by bacteria that use up the available dissolved oxygen within the water. This leads to more hypoxic and anoxic zones where dissolved oxygen levels are so low and unsuitable for fish habitability that it can even lead to mortality (with large incidents of mortality known as fish kills). In temperate lakes, this shift towards eutrophic systems can often result in the extirpation of economically important species such as salmonids in favor of small species like cyprinids and gizzard shad. (Jones et al., 2013). These have little to no economic value from a fisheries perspective, and would want to be avoided at all cost by fishery managers.

Climate change is predicted to play a larger role over time as increased temperatures will result in lower stream flows—increasing residence times of water and reducing the flushing of nutrients from the water, which increases trophic statuses. This uptick in nutrients and minerals often leads to the presence of algal blooms; these blooms are not only a visible nuisance for humans, but can also result in harmful ecological effects.

Figure 4-18. Example of a fish kill due to eutrophication creating an anoxic habitat. *What causes fish kills?* (n.d.). USGS. Retrieved July 29, 2021, from https://www.usgs.gov/special-topic/water-science-school/science/water-qa-what-causes-fish-kills?qt-science_center_objects=0#qt-science_center_objects

3.7.3 Vernal Pools and Amphibians

Scattered across Vermont's forested landscape are thousands of vernal pools—small, isolated depressions that fill with spring rains and snow melt, but dry by late summer. Created by glaciation more than 10,000 years ago during the Pleistocene era, these ephemeral wetlands provide critical breeding habitat for several amphibians and support an abundant and diverse invertebrate community, many of which would become locally extirpated without vernal pools. Although seemingly small and insignificant at first glance, vernal pools are keystone ecosystems that significantly influence the surrounding forest by "exporting" large amounts of biomass (in the form of post-metamorphic amphibians) from the aquatic system to the terrestrial environment. However, climate change could have profound effects on vernal pool functions, the impacts of which would undoubtedly extend into the surrounding landscape.

Hydroperiod (the length of time a pool contains water) is the most important abiotic factor affecting the composition and productivity of vernal pool-dependent wildlife (Semlitsch et al., 1996). Annual variation in hydroperiod is directly related to year-to-year changes in weather patterns, especially precipitation, as well as pool size and depth (Winter et al., 2001). A pool must hold water for at least three months following ice-out in order to support successful breeding of wood frog (*Lithobates sylvaticus*) and four months to support successful breeding of mole salamanders (*Ambystoma* spp.) (Brooks, 2004). At the same time, a pool must dry occasionally to exclude fish populations that could predate on these larval amphibians that evolved in fishless environments. Under current climate change scenarios of earlier and stronger evapotranspiration during the growing season, combined with frequent droughts and shifts in the timing of precipitation, it is likely that many pools will dry earlier and remain dry longer, resulting in an increase in the frequency of pool-breeding amphibian reproductive failures. While these species are well-adapted to a "boom-bust" cycle of recruitment, where partial or complete reproductive failures are offset by large cohorts in "boom" years, an increase in the frequency of "bust" years could limit the viability of many populations.

In Vermont, the majority (90%) of pools studied were less than ¼-acre in size and shallower than 2-feet in depth (Faccio et al., 2013). These small, shallow, abundant pools would be disproportionately affected by climate-induced changes to hydroperiod, resulting in the increased isolation of the larger, remaining pools that could serve as hydrologic refugia (Cartwright et al. 2021). Such isolation would affect the ability of juvenile amphibians to disperse between pools, impact genetic connectivity of populations, and limit the recolonization of pools where breeding populations have been extirpated—all of which are critical to the long-term viability of metapopulations.

Pool-breeding salamanders in the genus *Ambystoma*, including spotted, Jefferson, and blue-spotted, are fossorial outside of the brief egg-laying period in spring. Although it would seem that spending most of their lives underground would buffer them from the effects of climate change, a recent study in Ontario showed that body condition of spotted salamanders declined over a 12-year monitoring period (2008–2019) due, at least in-part, to increased summer and autumn temperatures (Moldowan et al. 2021).

Additionally, a reduction in snowpack could lead to increased winter mortality of several species of frogs, including wood frog, spring peeper (*Pseudacris crucifer*), and grey treefrog (*Hyla versicolor*). All three species hibernate just below the leaf litter on the forest floor. As the temperature drops below freezing, they flood their bloodstream with glucose—which serves as an antifreeze to protect their cells from damage, even while the frogs freeze solid and their hearts stop beating. However, the glucose only provides protection down to about 20°F, so they are completely reliant on an insulating blanket of snow to keep them alive on frigid winter nights (O’Connor and Rittenhouse, 2016).

Building Resilience

From a landscape perspective, Vermont is particularly focused on maintaining ecological functions and connectivity within its forests and waters, with many conservation biologists and landscape ecologists agreeing that development of a resilient ecosystem network can alleviate the effects of habitat fragmentation and climate change. In the face of rapid climate change, populations of species will likely shift their geographic ranges to landscapes with the least amount of habitat fragmentation. In order to develop a more resilient network, landscape management strategies such as development of wildlife corridors and riparian zones near water bodies are currently being maintained and introduced to Vermont’s ecosystems (Interview with Robert Zaino of VT Fish and Wildlife Department-Interviewed by George Ni, 11/3/2020).

3.8 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

Traceable Account 1.	
Key Message 1: As climate change worsens, 92 bird species of Vermont, including the iconic common loon and hermit thrush, are expected to disappear from the landscape within the next 25 years.	
Description of Evidence Base	Evidence for climate change projections and shifts to bird species' ranges were developed by the National Audubon Society for use in Audubon's report *Survival by Degrees: 389 Bird Species on the Brink*.
Major Uncertainties	Possibly missing/not considering all of the possible predictors and variables that might affect bird species distributions, especially specific bird species or geographic traits.
Description of Confidence and Likelihood	Overall, species distribution modeling coupled with the abundance of long-term monitoring projects, field experiments, and citizen science projects have generated strong evidence that bird species are heavily affected by climate change, and many bird species are at risk of having their ranges shifted and endangered as a result. There is *very high* confidence that shifts in global temperature and seasonality will have dramatic shifts to Vermont's bird species, resulting in extirpation and extinction of many species.

Traceable Account 2.	
Key Message 2: Increasing warming trends are expected to result in an increase in white-tailed deer population and a mirrored decrease in moose population, which may have long-term impacts on Vermont's forest composition. Managing social systems (e.g. hunting) to account for changing public tolerance and demand for deer may provide one avenue to minimize this risk if undertaken proactively.	
Description of Evidence Base	Annual harvest data of moose and deer hunting in Vermont was obtained from Vermont's Fish and Wildlife Department, with records spanning from 1900-2019. Multiple studies across northern latitudes indicate favorable conditions for white-tailed deer under climate change (Rodenhouse et al., 2009; Gaughan and Destefano, 2005). Nationwide and state-specific trends show declines in hunting participation since 1980(VT Fish and Wildlife Department, 2021b). However, public support for deer hunting in Vermont remains high (Boglioli, 2009; VT Fish and Wildlife Department, 2020).
Major Uncertainties	Harvest data alone is not necessarily an accurate depiction/substitute for demographic data. There are also implicit biases to the data (Harvest data implies a human-centric bias to the data as the occurrences/records are only the ones that were actually hunted by humans, so actual numbers are sure to vary).
Description of Confidence and Likelihood	While the harvest data alone does not give sufficient evidence of climate change's impacts on ungulate populations, studies done across North America have found sufficient evidence that white-tailed deer and moose populations have opposite reactions to common warming trends, and these dynamics have long-term impacts to forest composition and structure. As of right now there is *medium confidence* that white-tailed deer and moose populations have been affected until appropriate population data has been gathered. Sufficient hunting participation and public support for hunting are key if the practice is to remain a method for managing Vermont's deer population.

Traceable Account 3.	
Key Message 3: As warming trends reduce the severity of winters, the subsequent warming waters will have adverse effects on lake and river systems, including increased risk for harmful algal blooms (HABs) and reduced overall biodiversity and health in lake ecosystems.	
Description of Evidence Base	Evidence of warming lake temperatures come from numerous studies on Lake Champlain and other water bodies that have been conducted on climate change's impacts on aquatic ecosystems and limnology (Smetzer, 2012; Kaushal, 2012).
Major Uncertainties	Trends and annual water temperatures of Vermont's lakes and rivers are consistent and monitored through both government agencies and citizen science efforts. The full impact of these trends on overall aquatic health is unclear, as the creation of HABs is only partially affected by the annual water temperature.
Description of Confidence and Likelihood	Current efforts to monitor HABs in Vermont's lakes (Lake Champlain Basin Program) are keeping vigilant watch and recording data. There is high confidence that warming trends will result in overall increases in summer surface water temperatures, as well as increased precipitation and runoff events. According to the available research on HABs, it is possible that HABs may increase in frequency and intensity due to the flushing of nutrients into Vermont's waterways as well as increases in water temperature.

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4 AGRICULTURE AND FOOD SYSTEMS

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4.1 KEY MESSAGES

1. Vermont's climate is already changing in ways that benefit its agricultural system, including longer growing periods (freeze-free periods lengthened twenty-one days since early 1900s) and milder temperatures (annual average temperature increase of 2°F (1.1°C) since the 1990s), allowing farmers to experiment with new crops or practices not previously viable in Vermont.
2. The changing climate also brings agricultural setbacks, such as negative impacts on fruit-bearing species like apple trees that require a sufficient over-wintering period for success in the next growing season. The maple syrup industry is also at risk due to variations in winter temperatures.
3. Climate models predict tougher growing conditions due to greater variability in temperature and precipitation, including heavy precipitation and dry spells.
4. Vermont's average annual precipitation has increased 6.7 inches since the 1960s. Summer precipitation has increased most (additional 2.6 inches since 1960s) and is characterized by more heavy precipitation events (defined as more than one inch of precipitation in one day), although spring precipitation has also increased notably (additional 2.11 inches/year since 1960s, and 0.8 days/year with heavy precipitation). Spring precipitation accumulates in the soil and can make farm operations difficult. While precipitation during the growing season is trending upward, precipitation falls in fewer, more extreme events and is coupled with longer periods of no rain at times when crop water requirements are still high; thus, irrigation may become increasingly important.
5. At the Earth's surface, increasing concentrations of carbon dioxide may benefit yields in crops that utilize the C3 photosynthetic pathway (i.e., many of Vermont's forages) if conditions are otherwise ideal. Conversely, an increase in surface-level ozone concentrations may reduce crop productivity.
6. Extreme events are expected to increase. More periods of flooding and drought will lead to more crop damage or failure. Stormwater and irrigation infrastructure will be crucial in mitigating these effects.

7. Agriculture and food systems may play an important role in mitigating climate change, if mitigation provides financial opportunities, are distributed fairly and accurately, and are implemented with careful monitoring, reporting, and verification. Urban and suburban areas in Vermont have the potential to improve adaptation and mitigation of climate change by growing food closer to where it is consumed.

4.2 OVERVIEW

Agriculture has been, and remains, a defining characteristic of Vermont's landscape, culture, and economy. The state's food system has experienced tremendous growth over the past decade, as evidenced by the expansion of the food system's economic output by 48% from 2011 to 2020 (Kavet, 2020). By 2017, 13.9% of all in-state food purchases were comprised of Vermont's farm and food products (Willard et al., 2020). Despite this growth, climate change has the potential to significantly disrupt farm and food system profitability and viability. Multiple climate shocks are possible within single growing seasons, and climate change impacts occurring elsewhere in the country can have ripple effects in Vermont. Resilience measures are critical across this sector, but they will vary based on the specific type of enterprise or production system. Farmers and food system workers are not unfamiliar with challenges and change, and they have already demonstrated instances of successful and ingenious adaptation. As the data in this chapter show, individuals and businesses must operate and move forward knowing that they cannot plan for what was once known as "normal."

4.3 AGRICULTURE AND FOOD SYSTEMS IN A CHANGING CLIMATE

Impending climate change will increase precipitation and temperature variability and extreme events. These changes have the potential to both positively and negatively affect production agriculture and food systems in Vermont. Potential benefits and drawbacks are discussed in the following sections.

4.3.1 Freeze-Free Period

The freeze-free period is defined as the number of consecutive days in which the minimum temperature does not go below 28°F (-2.2°C). The length of the freeze-free period is not the same as the length of the growing season. The freeze-free period is used to assess how climate change will affect production agriculture. Statewide data from climate stations (see Climate Change in Vermont chapter) show a significant increasing trend in the length of the freeze-free period across the state. From 1960 to 2020, the freeze-free period increased at an average rate of 4.4 days per decade and accelerated to 9.0 days per decade since 1990 (Figure 5-1). Since the 1990s, the most dramatic freeze-free increase is observed in the Southern and East/Northeastern portions of the state (increase of 17 days and 18 days, respectively); the Western portion has increased 10 days. Farmers in Western Vermont (i.e., Champlain Valley) have experienced relatively modest changes, whereas farmers east of the Green Mountains and to the south are dealing with conditions that are quite different from what was “normal” thirty to fifty years ago. The historical observations suggest a strong trend that may continue over the next several decades. With continued climate change, the entire state can expect longer average freeze-free periods. However, farms— depending on their location—will have more pronounced impacts.

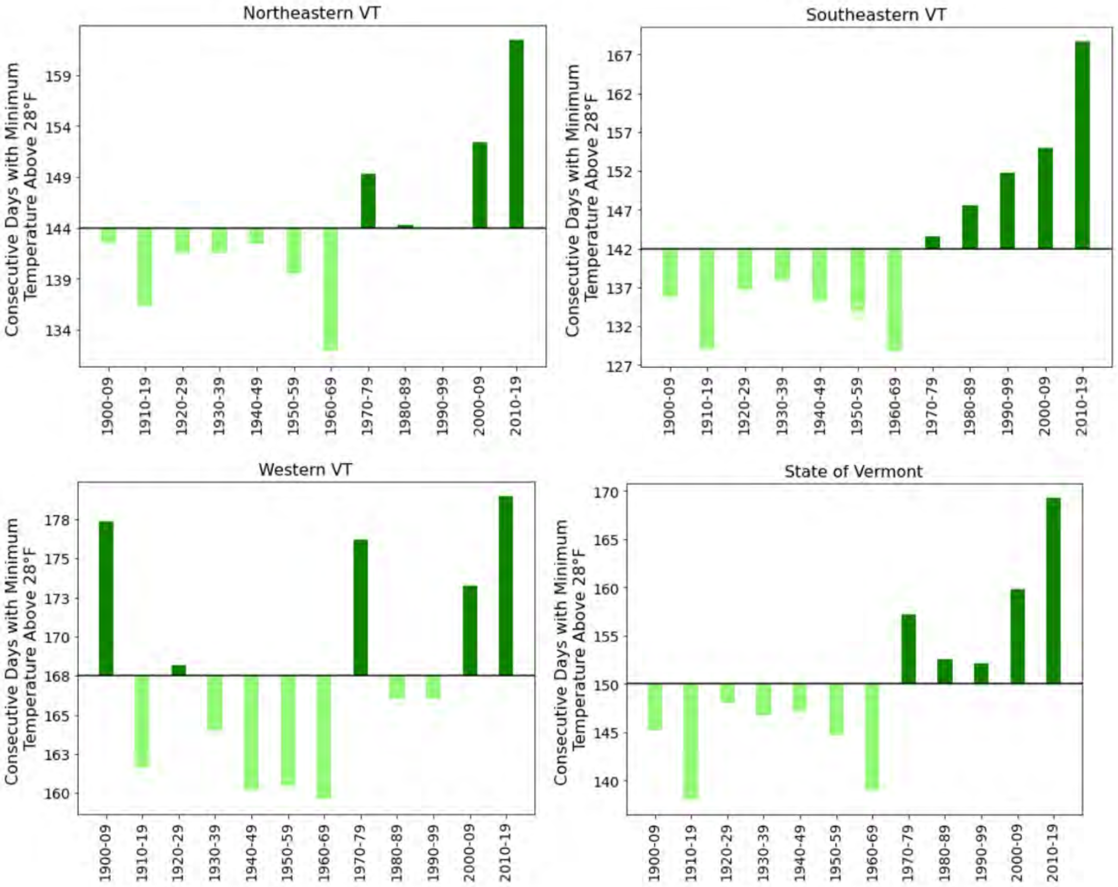


Figure 5-1: Decadal averages of Vermont's freeze-free period

Note: The freeze-free period is calculated based on the number of consecutive days with minimum temperature above 28ºF (-2.2°C). In this figure, the decadal average is plotted above or below the 1900–2019 mean (solid black line) for a) Northeastern Vermont, b) Southeastern Vermont, c) Western Vermont, and d) State of Vermont (Figure 1-10, Climate Change in Vermont chapter). Note the differences in y-axis ranges.

Simulations of future freeze-free periods from a conservative climate change scenario (RCP 4.5) estimate an additional 12-20 days by 2069 relative to 1979-2008 (Figure 5-2). This may lead to increased yields for farmers and/or allow for cultivation of new crops that previously would not have been successful in Vermont. The list of new crop options is likely to evolve over time, as farmers and researchers explore the possibilities. For example, efforts to grow saffron outdoors are underway, and research shows it is economically viable in the state (https://www.uvm.edu/~saffron/). Saffron is the most expensive spice in the world and previously was grown only in warm climates near the Mediterranean and in India.

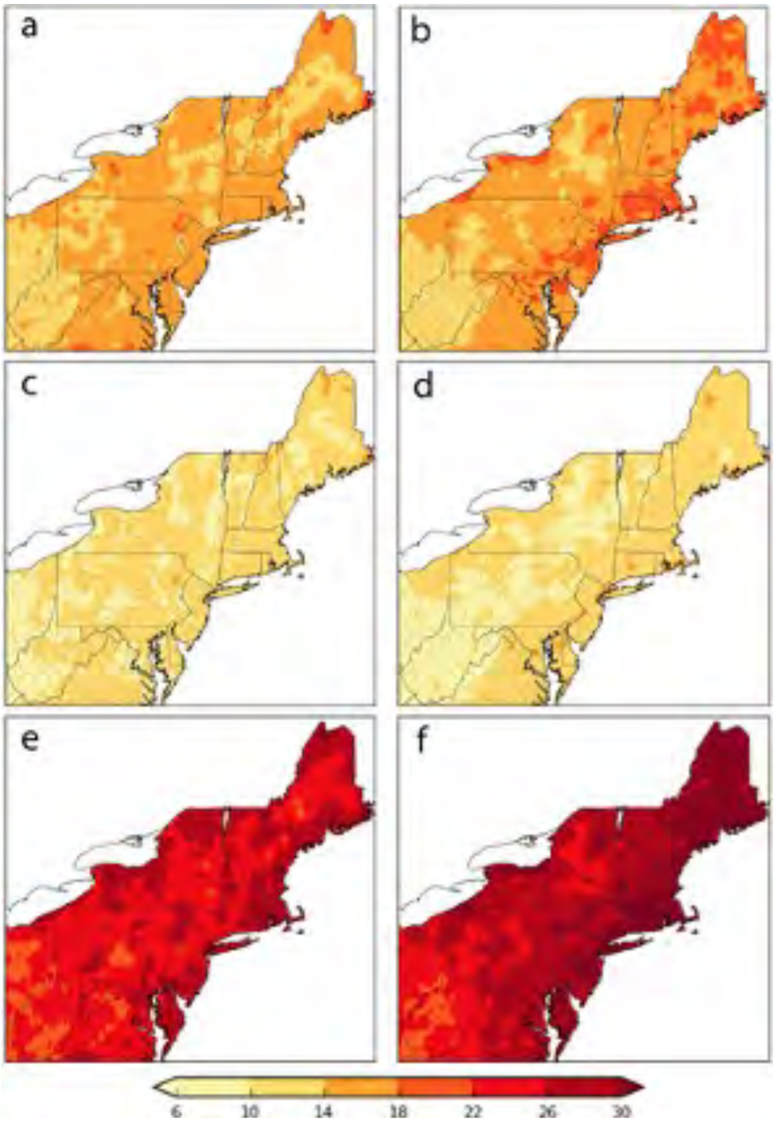


Figure 5-2: Model estimates of change in the period between the last freezing day in spring (right column) and first freezing day in fall (left column).

Note: Freezing is defined as -32°F (0°C). Comparison period is 1979-2008. Models used are: a, b) 2040–2069 RCP8.5; c, d) 2040–2069 RCP4.5; and e, f) 2070–2099 RCP8.5. Adapted from Wolfe et al. 2018.

A later first-frost will extend the growing season for both annual and perennial crops in Vermont (Wolfe et al., 2018). This will increase harvest flexibility, giving forage crops extra time to accumulate biomass, especially important if planting was delayed in spring. Late first fall frosts may create opportunities for later harvests (i.e., tomatoes, cut flowers, fall raspberries, or additional cuttings of hayfields). It may also be possible for double cropping (two crops per field in one growing season) to occur. Other factors, such as excess moisture, also affect spring farming practices. Bare soils prior to planting in the spring do not have plants to return soil moisture to the atmosphere through transpiration, so moisture accumulates in the soil and increases risks of compacting soil or damaging (i.e., rutting) fields if heavy machinery is operated (i.e., to terminate a cover crop or plant) or of damaging machinery. Thus, a longer freeze-free period does not necessarily mean farmers will be able to plant sooner. The benefit of a longer growing season may be offset by the trends in springtime precipitation.

4.3.2 Water

4.3.2.1 Spring Precipitation

Previous trends in spring precipitation in New England show that bulk precipitation in the twenty-one days leading up to the spring thaw has increased (Figure 5-3). Climate models project this trend will continue at an alarming rate (Wolfe et al., 2018). This is a classic representation of how climate change is impacting Vermont and the rest of the world: the extremes become more extreme. Spring is notorious in Vermont for being the wet (mud) season, and that is likely to stay the case as the climate changes.

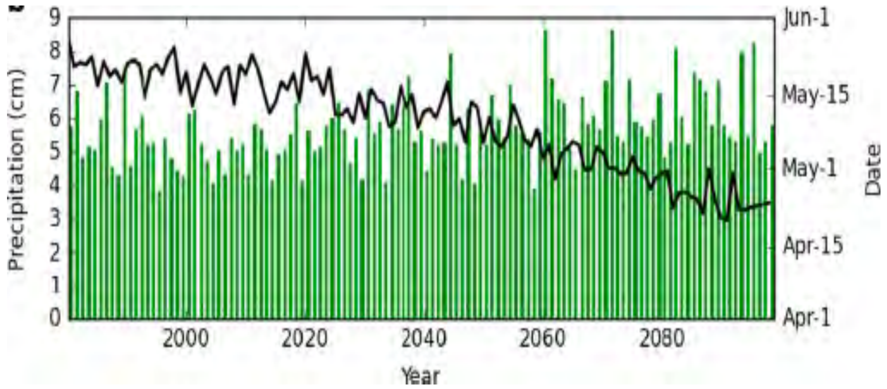


Figure 5-3: Last frost date (black line) and rainfall (green bars) over the twenty-one days preceding last frost in Burlington, Vermont

Note: Data is from observed historical data and simulated future climate scenario based on RCP8.5. Adapted from “Unique challenges and opportunities for northeastern US crop production in a changing climate” by Wolfe et al., 2018).

4.3.2.2 Tile Drainage

Farmers in Vermont have adapted to the wet conditions in spring by using artificial subsurface tile drainage. Originally used to drain wetlands in the midwestern United States, tile drains are perforated plastic pipes that are installed to a depth of one meter to remove excess water from the soil, thereby improving farm operations and crop productivity (Madramootoo, 1999). Vermont farmers who have not tiled their fields may do so to adapt to climate change. Usually tile drains are used on finely textured, poorly drained soils that are at risk for low yield and soil compaction because of excess moisture. Many of the farms in the Champlain Valley are located on these types of soils, and tile drainage has been shown to be an effective method for improving trafficability and growing conditions in field crops and vegetable systems (King et al., 2015). Tile drainage systems also have been shown to transport nutrients more rapidly through the subsurface, raising water quality concerns. To address these concerns, alternative soil and nutrient management practices can be implemented, or tile drainage systems can be modified with drainage water management structures to control the height of the water table in fields. Some studies have found that these structures reduce nutrient and sediment loss during extreme events (Tan and Zhang, 2011). Other methods of removing excess water include surface-grading and ditching fields. Research regarding the environmental impacts of tile drainage systems is ongoing in Vermont (Moore, 2016).

4.3.2.3 Water Stress and Irrigation

As discussed in the Climate Change in Vermont chapter of this report, summer precipitation has increased in recent decades, but it has also become increasingly variable. Timing of precipitation during summer months is and will continue to be irregular. It is likely that heavy precipitation events (greater than one inch of precipitation per day) will supply much of summer precipitation, which means farmers will need to adjust their stormwater infrastructure for larger runoff events. Farmers can work with state and federal agencies to engineer, permit, and cost-share stormwater infrastructure improvements.

Farmers also need to prepare for increased frequency of prolonged dry spells or droughts. Even if farmers invest more in irrigation infrastructure, there might be limitations on water access. While summer stream low flow has not shown any significant decreasing trend in

Vermont (see Water Resources chapter), reduced pond storage and dry wells may occur in years of drought, and stream base flow may be reduced. It is worth noting that most wells in Vermont are not on highly desirable geology; that is, they are not apt to be high producing water sources for future water needs (see Water Resources chapter). Farmers cannot make surface withdrawals from streams when flow rates fall below the threshold set for preserving wildlife (Armstrong et al., 2001). While it is difficult to anticipate the timing of individual farms' water stress, periods of crop water stress are likely to occur for farms simultaneously throughout a region. Farmers can prepare for low water availability by using seasonal potential evapotranspiration (PET) computer simulation models, staying current with the Vermont drought conditions monitor (https://www.drought.gov/states/vermont/), and working with other farms to strategically plan water delivery services. Farmers should also consider using remotely monitored soil moisture sensors to understand how stressed their crops are in real time. Cost share programs would be beneficial to allow farmers to employ this equipment without as much financial and operational burden.

Water for irrigation may remain sufficient for Vermont producers; however, the temporal distribution and disruptions of future precipitation are subject to much variation. Recent trends show increasing precipitation in all seasons, with the greatest rate of increase in summer precipitation, and they show increased variability and frequency of dry spells (see Climate Change in Vermont chapter). Increasing precipitation does not mean farmers will require less irrigation; in fact, sprinkler irrigation in Vermont has increased from 1985 to 2015 at the same time precipitation increased (Figure 5-4) (USGS, 2021b; see Climate Change in Vermont chapter). It is likely the need for irrigation will continue to increase because of increasingly variable precipitation. Heavy precipitation events are expected to bring much of any given season's total precipitation, which is not as helpful during the growing season as frequent, smaller precipitation events. The length of dry periods will also increase, which may force farmers to irrigate (Trenberth, 2011). Climate models suggest that by 2050 the amount of monthly precipitation during the growing season (summer) will be less on average than in the period 1980-1999 (Figure 5-5) (USGS, 2021a).

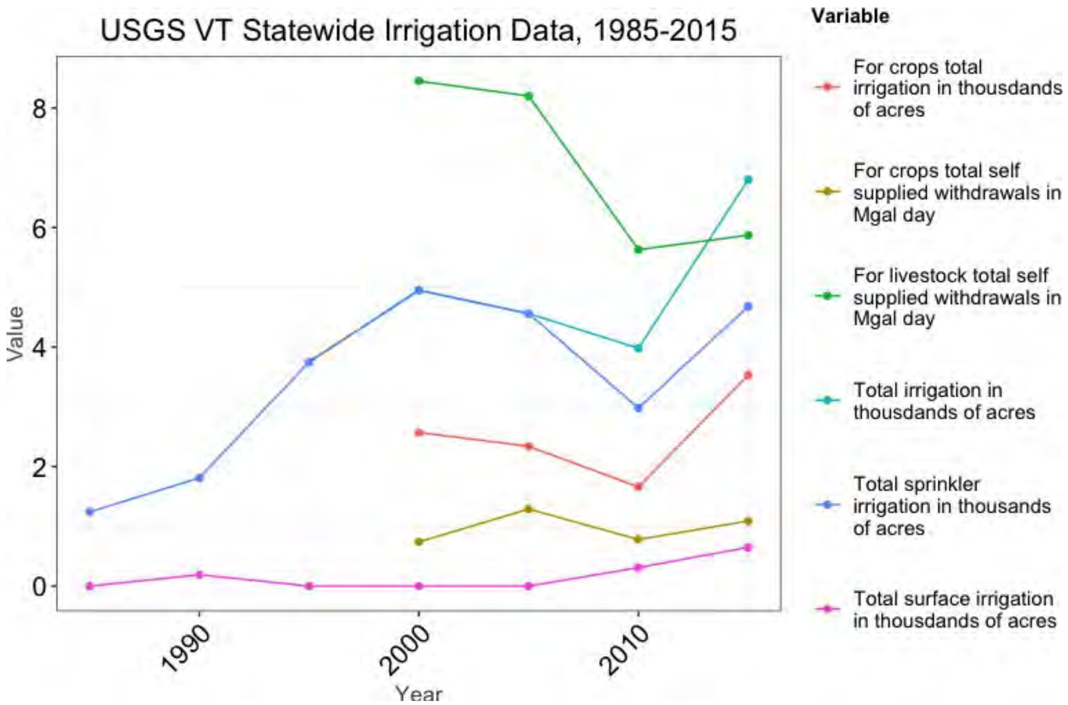


Figure 5-4: Irrigation stats in Vermont from 1985-2015. Total self supplied withdrawals are surface and groundwater combined (REF USGS, 2021). Data every 5 years.

Note: Data represents surface and groundwater combined withdrawals (self-supplied) reported every 5 years (USGS, 2021b).

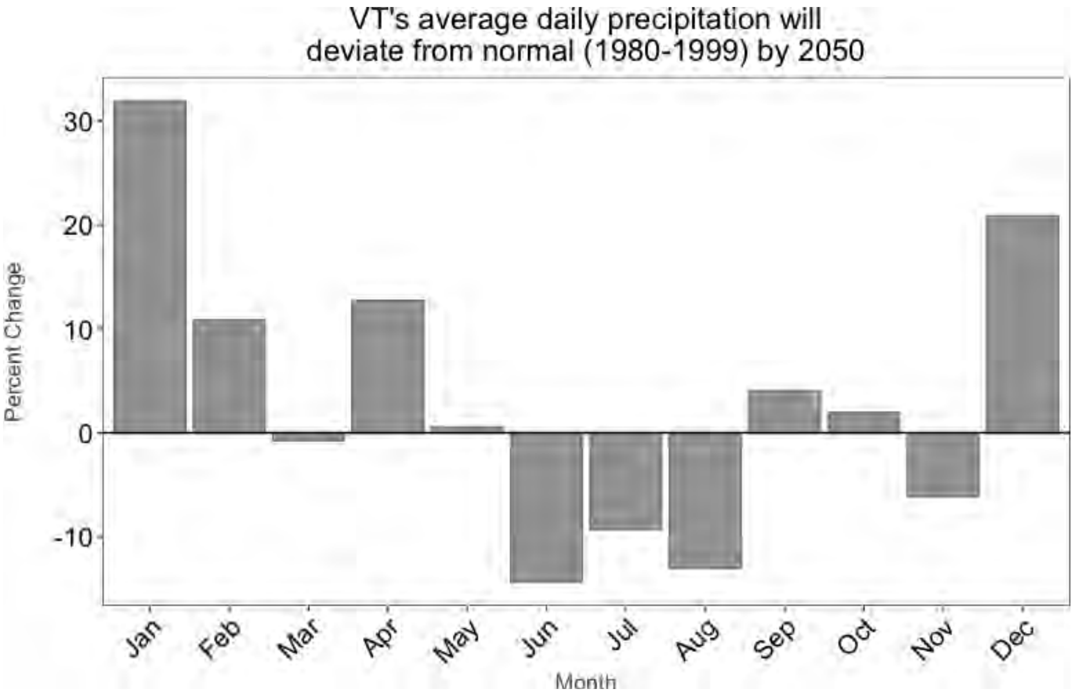


Figure 5-5: Projected daily mean precipitation in 2050 as percent deviation relative to 1980s–1990s shows lower summer growing season precipitation (USGS, 2021a)

Groundwater and surface water withdrawals for livestock decreased from 8.45 million gallons (Mgal) per day in 2000 to 5.87 Mgal per day in 2015, though an increase was observed from 2010 to 2015 (Figure 5-4) (USGS, 2021b). In Vermont, self-supplied water withdrawals for livestock are greater than that for crops. Peak groundwater usage may increase during summer months when surface water withdrawal from streams and ponds are no longer available due to limits for wildlife conservation. While trends in overall moisture suggest there will be sufficient groundwater in Vermont, farms will still need to adapt to the increased energy costs associated with higher rates of groundwater extraction.

4.3.2.4 Flooding

Increased precipitation, particularly periods of heavy precipitation events, are leading to increased flooding in Vermont (see Water Resources chapter). Farms located within floodplains will continue to be at risk as more extreme and unpredictable flood events occur. In addition, farms outside of floodplains (designated 25- or 50-year return period) may experience more frequent floods (Wolfe et al., 2018). Flooding during the growing season can be devastating— due to potential contamination with human waste, heavy metals, etc., even crops that survive may not be allowed to enter the human or animal food supply if the edible portion has been in contact with flood waters. If flood waters have not directly contacted the edible portion, there are certain measures farmers can take to ‘save’ the crop; however, usage is determined on a case-by-case basis. Flooded produce is covered in depth by the UVM Extension FAQ about handling flooded produce (Nickerson et al., 2013).

Box 5.1: Halloween 2019 Floods in Vermont

A 2019 Halloween storm created major agriculture losses, even though the event occurred outside of the major growing season. For example, Maple Wind Farm in Richmond lost 2,000 turkeys and chickens (unfortunate timing due to the approaching Thanksgiving holiday) when the Winooski River rose at an astonishing rate. This contributed to a significant loss of income during the winter season. Other farms, like Boston Post Dairy Farm, had haybales displaced and contaminated by floodwaters.

However, impacts were minimal at the Intervale Farm, where farmers gathered last minute support from the Burlington community to mass harvest remaining frost-hardy crops before the flood hit. As this area is within the known Winooski floodplain, farmers there are accustomed to watching the river hydrograph for rising floodwaters. All farms in floodplains could benefit from flood mitigation protocols like those used at the Intervale.

4.3.2.5 Water Stress

Drought conditions will become more variable, with water deficits occurring and accumulating during the non-growing season when soils and surface waters are typically recharged. Droughts often carry over from one year to the next, or a drought may begin in the winter, such as in parts of Vermont in 2002, 2012, 2013, 2015, and 2017. As of May 2021, 75% of the state was in moderate drought, and the entire state was classified as abnormally dry (National Integrated Drought Information System, n.d.). Droughts also occurred in much of the state during the 2016, 2018, and 2020 growing seasons. In 2020, farmers in at least ten Vermont counties were eligible for federal aid for crop loss due to the drought; losses were estimated at $27 million (McCallum, 2020).

4.3.3 Warmer Temperatures and Temperature Variation

During the growing season, warmer temperatures, including heat waves and warmer overnight temperatures, are expected (see Climate Change in Vermont chapter). Warmer temperatures benefit existing crops, offer success with new crops, and may make double cropping possible. Dairy farmers may be able to plant more productive field crop varieties as well. Warmer temperatures will also result in increased livestock stress and a need for additional cooling infrastructure, including shade structures for pasture-based operations. Warmer temperatures also promote evapotranspiration and can stress crops at vulnerable times.

Crop stress is likely to increase during the spring because of increased variation in springtime temperatures and will have the greatest impact on cash crops. Once fruiting crops meet their winter chilling requirements, they will bud once temperatures warm, but cold temperatures following a warm period can damage buds or even cause crop failures (Stafne, 2020). Warm winter days, defined as days with temperatures of greater than 50°F (10°C), in Vermont have increased by 1.82 days between the 1960s and 2020. Cold winter nights, defined as a minimum temperature of 0°F (-17.8°C), have decreased more substantially, by10.01 days (see Climate Change in Vermont chapter). Trends suggest warmer winters will continue in Vermont, although it may be several decades before crops like apples (which has one of the strongest chilling requirements of fruiting bearing species) will suffer the effects of insufficient overwintering. This may be a problem first in southern Vermont, where warming trends are more pronounced. The most pressing issue all farmers will have to deal with is fluctuations in late winter/early spring temperatures that result in budding with subsequent frost periods. This can be devastating for crops that respond more rapidly to brief periods of warming, so farmers will have to adapt by selecting varieties that tolerate temperature fluctuations better (Wolfe et al., 2018). Also see the following section on pest pressures.

4.3.4 Changing atmospheric conditions and pest pressures

Globally, pest pressures on agriculture are changing with climate, providing clues to the challenges Vermont may face. Despite improvements to pest and disease management technology, global crop production loss due to pathogens is estimated at 10-16% (Chakraborty and Newton, 2011). A challenge caused by climate change is shifting atmospheric conditions, specifically concentrations of CO_2 and ozone that can affect crop diseases and productivity. Pests and diseases with expanded range, increased competitiveness, or other advantages are expected to put increasing pressure on crops as well. A lack in genetic diversity of cash crops means they will fatigue quicker than weeds, pests, and diseases, which can mutate and adapt more rapidly to climate change (Raza et al., 2019).

Continued increases in atmospheric CO_2 concentrations can enhance photosynthesis and may result in higher yields for crops (i.e., high quality forages). The benefits from increased CO_2 may be offset by the damage occurring from increased surface-level ozone, which can increase disease expression and thus decrease crop productivity (Eastburn et al., 2010). Ozone-related damage and decreased productivity varies with crop species—many Vermont crops are considered ozone-sensitive, including forages, fruit bushes, grapes, lettuce, potato, spinach, tomato, and watermelon. In contrast, certain vegetable crops like strawberries and tomatoes grown in the presence of elevated ozone had increased concentrations of nutrients like vitamin C and β-carotene, respectively (Moretti et al., 2010).

The impact climate change will have on pests is a function of the expected increase in CO_2 concentrations and temperatures. One plant response to increased CO_2 is an increase in foliar carbon:nitrogen ratios. For example, reduced foliar nitrogen in bell pepper plants due to elevated CO_2 concentrations caused reproduction setbacks for phloem-feeding insects by 37%, yet their feeding was unaffected (Dáder et al., 2016). While some leaf-chewing insects have been found to suffer reproduction setbacks up to 34%, other insects in this category may benefit (Robinson et al., 2012). For hemipterian species (also known as “true bugs”) that feed on plant sap, increased CO_2 resulted in both increased and decreased animal counts, depending on the hay and garden crops and the different species of this order (Guo et al., 2014; Oehme et al., 2013). These studies indicate that some pests will have reproductive setbacks, but others may benefit.

Temperature changes may impact insects’ life cycles and activities. Some insect orders cannot reproduce beyond a certain temperature threshold, so increased temperatures will result in reduced populations. However, insects may be able to adapt their reproductive window or increase their temperature thresholds if change occurs gradually (Debarro and Maelzer, 1993). Insects also have an upper temperature threshold for flight, which will ultimately affect migration and daily activity (Trębicki and Finlay, 2018). Temperature changes also can influence the number of generations and species distribution (Trębicki and Finlay, 2018).

Insects in Vermont are likely to be impacted in the same physiological ways; however, the degree of pest adaptation is still unknown. Vermont can expect an increase in new pest and disease species that formerly were limited to southern latitudes; this already has been the case with more mild non-growing season conditions in the forest sector (see Climate Change in Forests chapter). More research and a holistic approach to pest and disease management are required for Vermont to best adapt to climate change.

The uncertainty around pest changes is similar for disease changes. For example, the threat of fire blight caused by the bacteria (Erwinia amylovora) increases with warmer spring temperatures, resulting in greater risk of earlier blooming during rain events for crops such as apples and pears. After entering the plant via the flower, fire blight kills vascular plant tissue, leading to a loss of limbs or whole tree mortality. In Switzerland, Hirschi et al. (2012) showed that the effect of earlier blooming on fire blight was offset by changing trends in spring precipitation in some regions of the country, while the southern regions had significant increases in fire blight. As a sporadic and climate-related disease, the impact of fire blight may be erratic in Vermont, but it is known to occur increasingly in New England (Bradshaw, 2016).

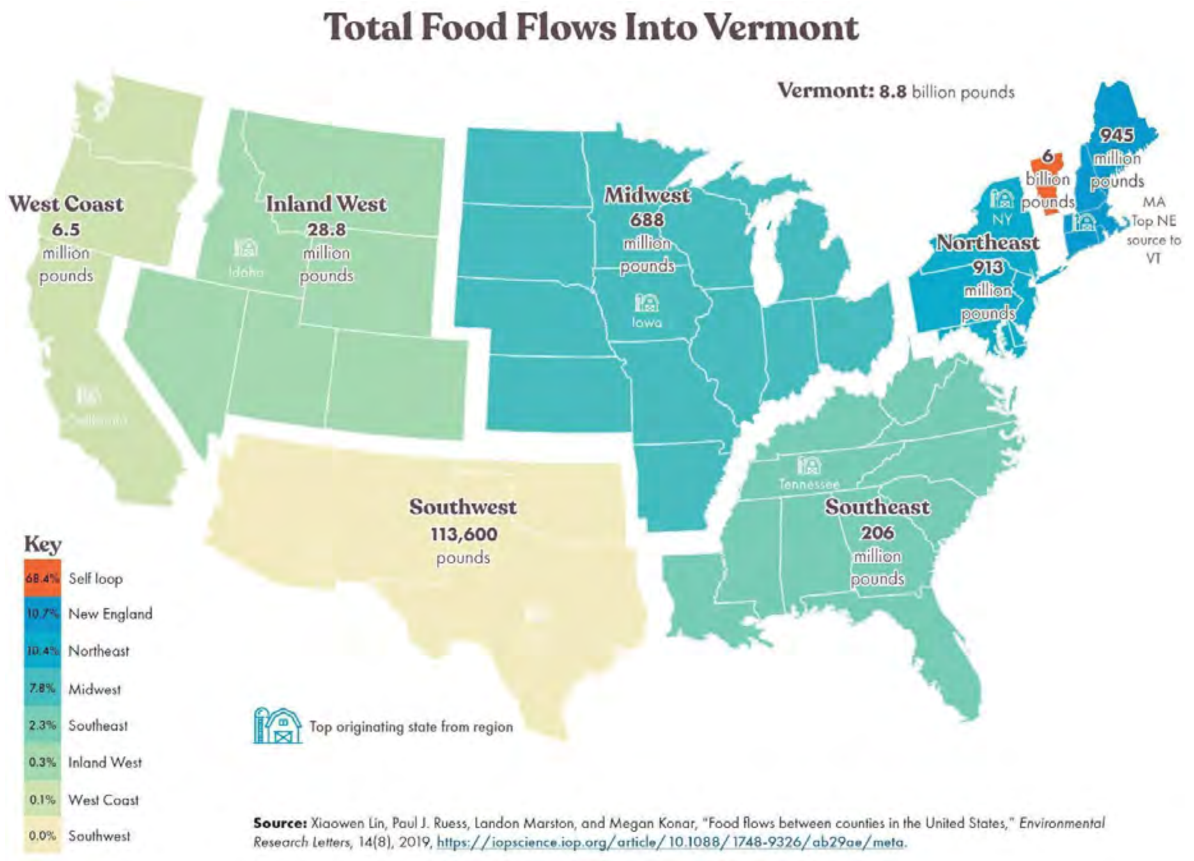
4.4 MITIGATION, RESILIENCE, AND ADAPTATION

This section discusses how the agricultural and food systems in Vermont can adapt to climate change, informed by how other systems around the world have and continue to adapt.

4.4.1 Food Systems in a Climate-Conscious State

Vermont's food system is critical to its economy, identity, and quality of life. While food is rightfully associated with farming, the food system in its entirety encompasses a complex network of resources, activities, and people that extend beyond our farmland. The food system, in addition to farmers and farmland, includes processing; distribution; various market channels and their consumers (e.g., farmer's markets, institutions, grocery stores, restaurants); food waste management; the support system of nonprofits, government agencies, educational institutions, and funders and investors; and the people (e.g., farmers, food workers, policy makers, consumers) involved in all these activities. From an economic perspective, these interacting pieces generate $11.3 billion and employ more than 64,000 Vermonters. In one way or another, we are all participants in the Vermont food system.

Given the significant footprint of the food system in Vermont; its importance in contributing to the state's and region's food security; and its far reaching influence on our economy, environment, and culture; Vermont's ability to successfully mitigate and adapt to climate change requires an integrated understanding of the myriad ways in which the food system contributes to, is affected by, and can provide mitigative, adaptive, and resilient climate solutions for Vermont in what is an era of increasing climate disruption. Developing a climate-smart food system cannot solely rely on policies, innovation, and management focused on the farm gate—though farm-based climate solutions are necessary—but it also must account for and address interdependencies among inputs, production, processing, distribution, point of sale (i.e., markets), consumption, and waste management. For example, in examining where food is coming from and what is coming from elsewhere, the state can begin to imagine and plan for scenarios in which food access decreases or is at risk due to food chain disruptions in other parts of the country (due to crop failures, labor shortages, damaged infrastructure etc.). The food flows analysis provides a window into the complexity of America's food system and Vermont's (and New England's) reliance on certain regions or states (Figure 5-6).



Total Food Flows Into Vermont

Source: Xiaowen Lin, Paul J. Ruess, Landon Marston, and Megan Konar, "Food flows between counties in the United States," *Environmental Research Letters*, 14(8), 2019, https://iopscience.iop.org/article/10.1088/1748-9326/ab29ae/meta.

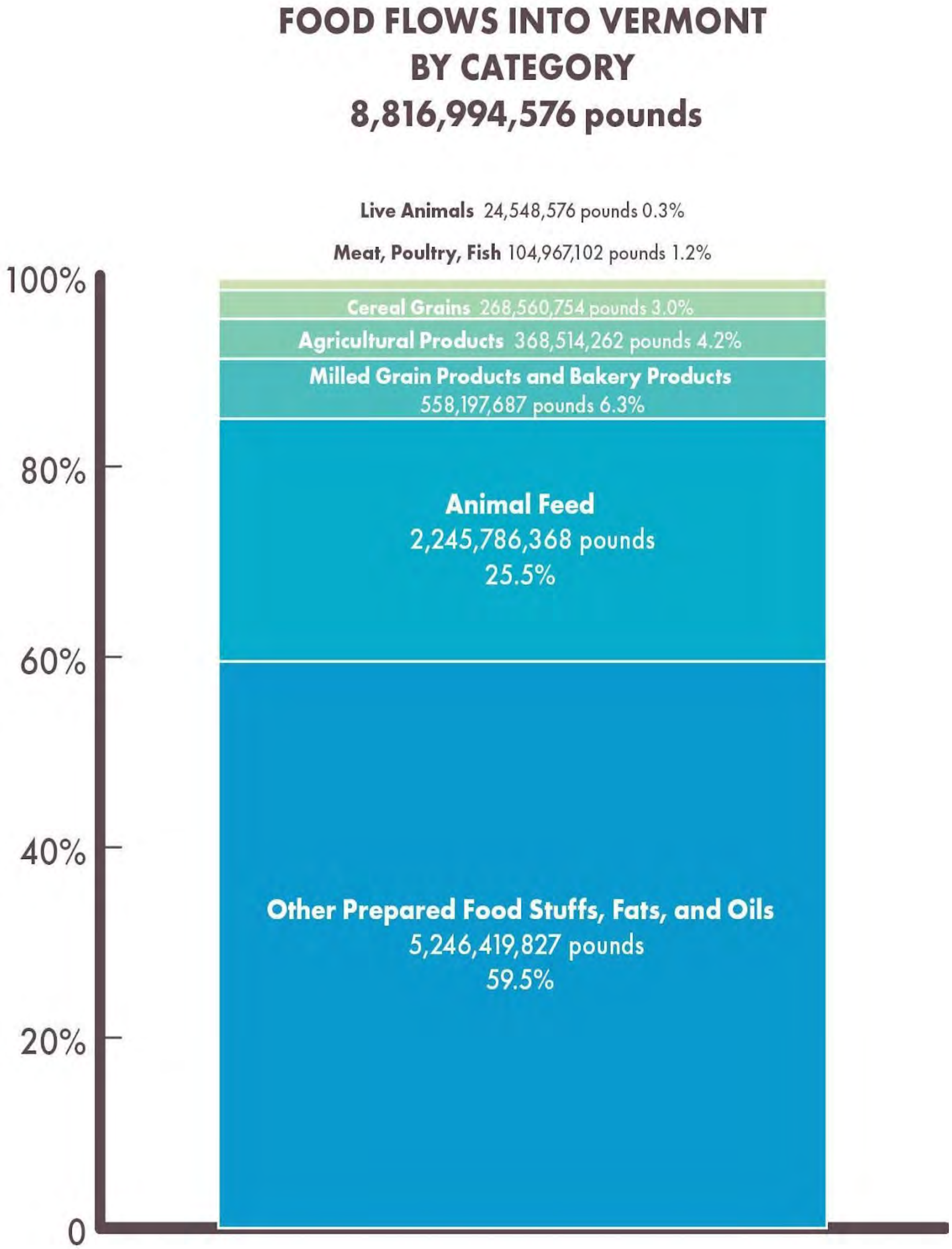


Figure 5-6: Total food flows into Vermont by region (top) and category (bottom)

Note: The food flows analysis is about the transportation of food, not about production or consumption per se. It's suggestive of an order of magnitude of food that enters and moves around between and within states, helping to better conceptualize supply chain vulnerabilities and risks of regions, particularly as they relate to climate change, economic disruption, and Covid-19 or future pandemics. Modified after Lin et al. 2019.

Each component of the food systems supply chain has a part to play in mitigating climate change, but each component also must be prepared to adapt to and withstand the impacts of climate to ensure the viability and security of the food supply. For example, food manufacturing—Vermont's second largest manufacturing industry—can improve mitigative capacity by adopting more energy-efficient processes and technologies and utilizing renewable energy. Planning and investment are also needed to increase the industry's adaptive capacity through: making facilities more resilient to extreme weather (particularly flooding), improved packaging that reduces waste and maintains quality and safety (particularly in extreme heat), and diversifying ingredient suppliers through local and regional supply chain development to reduce over-reliance on global supply chains that will face climate disruption. This is one example; of course, there are many more examples to draw from and questions that arise as the entire food supply chain is examined. For example, how can transportation emissions be reduced through accelerated adoption of electric vehicles and more efficient aggregation and storage infrastructure? How can distribution be more adaptive and resilient to climate disruption through greater logistics coordination? How can roads themselves be improved to withstand extreme weather to limit delivery delays to both commercial and charitable food sites? In what ways can energy use, particularly for refrigeration, be more efficient? What kind of additional incentives, technical and business support services, and training are needed to help farm and food businesses address these issues?

These are all critical questions to answer, yet beyond farming there is a relative dearth of available data regarding baseline food system emissions and potential for emission reductions and little evaluation of the preparedness and adaptive capacity of food processing, distribution, point of sale, and waste management systems. However, Vermont's Agriculture and Food System Strategic Plan 2021-2030 provides a roadmap to address these questions in a systemic way by articulating the vision, goals, and strategies that aim to put the state on a path to developing a climate-smart food system by 2030 (Willard et al., 2020). To do so, priority strategies from the Plan emphasize the need for increased, improved, and energy-efficient processing infrastructure; greater aggregation and distribution coordination and infrastructure; increased incentives and research for climate-adaptive practices; food security planning that ensures the Vermont food supply is sufficient to withstand global or national food supply chain disruptions caused by climate change; food system mapping that accounts for predicted climate impacts in order to aid state and municipal planning and investments; and increased professional development for technical assistance and business planning providers in order to help their farm and food business clients address and integrate climate change issues into management decisions and long-term planning.

4.4.2 Adaptation

Though farmers in Vermont have some options when it comes to adapting to climate change, economics emerges as a major barrier to adaptation, as it currently is cheaper for farmers to operate in a business-as-usual manner. Many farmers are climate conscious because they understand the impact climate has on their bottom line (Figure 5-7) (USDA FSA). Cost sharing, or government payments to help install conservation practices, is a way farmers can experiment with well researched best management practices (BMP) that will increase resilience to and mitigation of climate change with less of a financial burden. Farmers would rather preserve the environment than put it in jeopardy, but they only can adopt practices if they are able to financially.

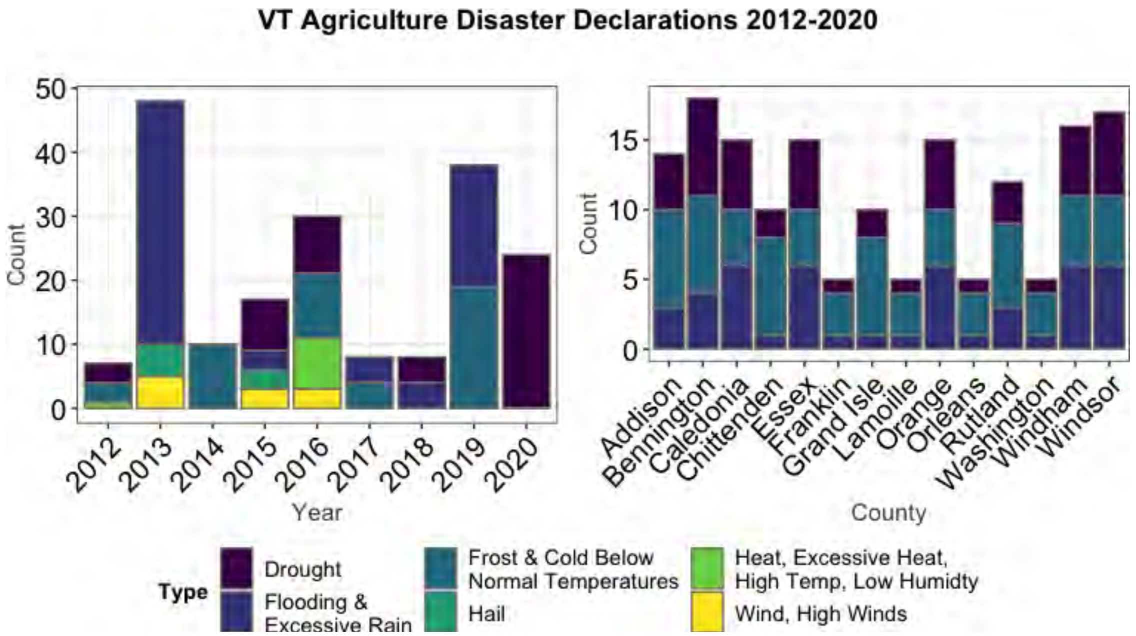


Figure 5-7: Agriculture disaster declarations 2010-2020

Note: Some counties have more than one disaster type per year. Source: USDA FSA.

4.4.3 Vermont Farmer Survey Data

Vermont farmers are adapting to climate change impacts based on previous experiences with weather extremes and perceptions of increases of extreme weather. Of the sixty-four Vermont farmers who responded to the New England Adaptation Survey, 65% made management changes due to an experience with drought, 56% were planning to make changes to their farms to manage for the risk of increased incidence of drought, 77% made changes due to experiences with extreme precipitation and flooding, and 64% were planning to make changes to address the risk of increased incidence of extreme precipitation events.

Farmers have primarily invested in soil health and conservation practices to help them address the risks of extreme precipitation associated with climate change (Figure 5-8). Additionally, farmers identified a wide range of practices and strategies they planned to employ based on their experiences with extreme weather, from changes in cropping systems to water catchment systems, irrigation, and hoop houses (White et al. 2018). While crop insurance is a strategy employed by large farmers in other regions (Mase et al. 2017), small and diversified farms in Vermont report low rates of crop insurance use to address weather extremes (Figure 5-8).

Most farmers in the region understand their vulnerability to the extreme weather associated with climate change, but they report that they lack the technical skills and financial capacity to adequately address climate-related risks and invest in adaptation (White et al. 2018). Research in Vermont identifies a gap in access to consistent and committed financial tools to support farmers' capacity to adapt to climate change (White, 2021; White et al., 2018). In focus groups, producers identified alternative financial safety nets such as community-supported agriculture groups and emergency relief funds as critical to supporting financial viability of their small and diversified farms (White and Pankoff, 2019). Farmers have also identified interest and willingness to participate in payment for ecosystem services (PES) schemes to address both climate adaptation and mitigation (White, 2021; White and Faulkner, 2019). In the last few years, a wide range of stakeholders has put effort into exploring the real potential for a healthy soils PES system to meet multiple goals, including resilience to climate change, increased carbon sequestration, and enhanced water quality (VAAFM, 2020). A legislature-mandated working group currently is working to make recommendations for a PES program.

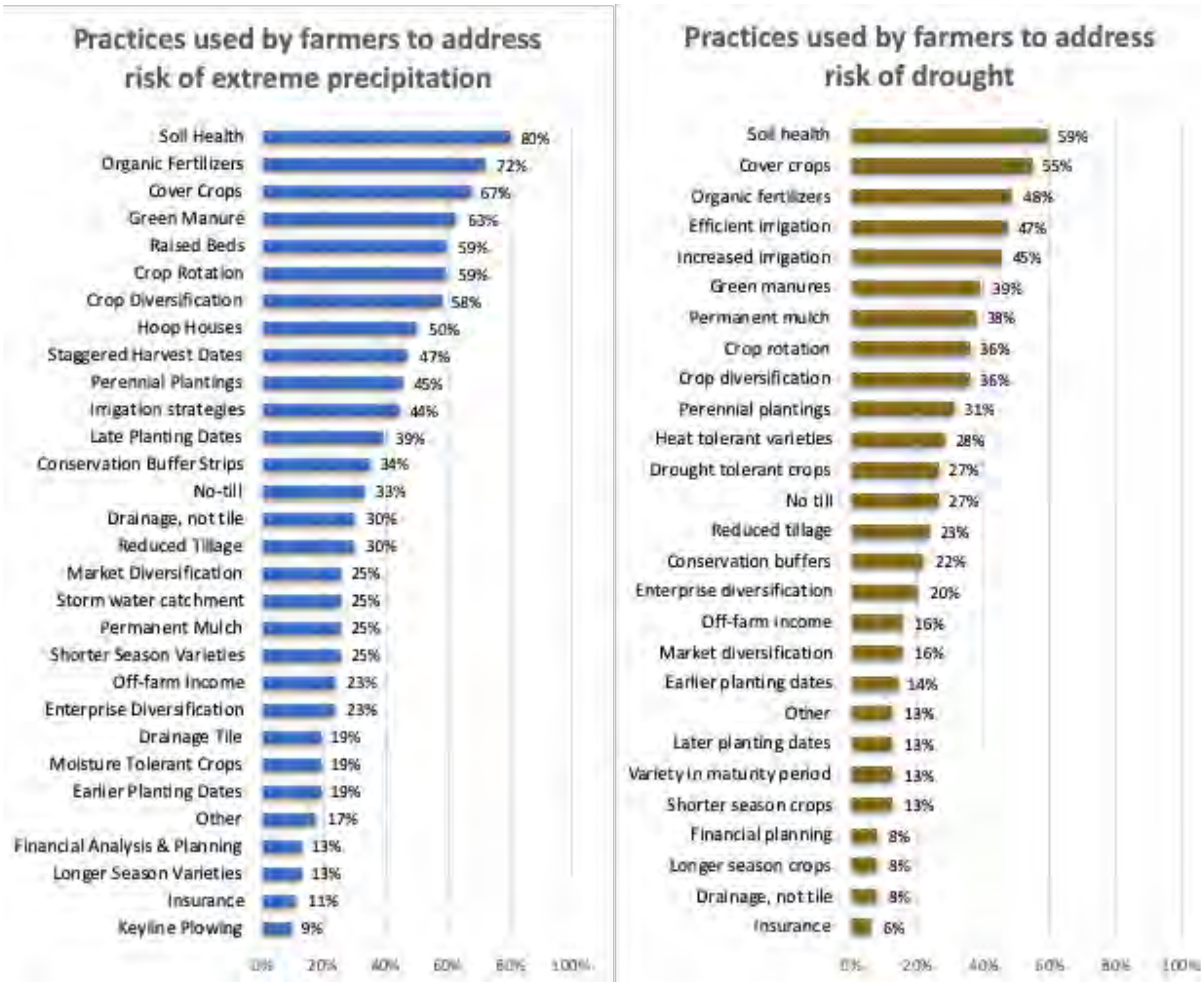


Figure 5-8: Practices used by Vermont vegetable and berry farmers to address risks of extreme precipitation and drought

Note: Based on responses of sixty-four farmers to the New England Adaptation Survey (White et al., 2018)

4.4.4 Mitigation

Vermont farmers are aware of their environmental footprint and strive to be environmental stewards when they have the financial capacity to do so (White et al., 2018). Climate change mitigation is often considered in decisions around tractor fuel consumption, greenhouse heat sources, and purchases of agricultural plastics such as plastic mulch, irrigation equipment, and tarps. Vermont farmers have expressed a high level of interest in new programs that would compensate them to manage their farms for enhanced climate regulation or ecosystem services (White and Faulkner, 2019).

4.4.5 Seed Systems

Seed systems (formal or informal activities related to production, dissemination, and access to seeds) present a critical entry point from which broad-ranging food system challenges can be addressed. In middle- and low-income countries, informal seed systems maintained by farmers often house higher degrees of crop intra- and inter-specific diversity (Croft et al., 2018) The diversity of seeds supplies essential ecosystem services and can act as a buffer in the face of climate risks. Such ecosystem services include disease and pest suppression, resilience to climate variability, and agrobiodiversity conservation (Pautasso et al., 2013). Moreover, through continued on-farm cultivation and subsequent saving and sharing of important traditional varieties and landraces, informal seed systems allow for the continued evolution and adaptation of crops to local conditions and to changing climatic pressures (Bellon et al., 2018).

In contrast, formal seed systems are dominated by commercial seed companies and are often marked by high degrees of vertical integration, regulation, and uniformity (Gill et al., 2013). Particularly prominent in high-income countries such as the U.S., formal seed systems often perpetuate conventional agricultural practices whereby producers try to alter agricultural landscapes to model the lab conditions (fertilizers, pesticides, irrigation) in which the seeds were bred. This inadvertently leads to environmental issues (Evenson, 2003) and hinders the ability of crops to interact with symbiotic organisms (Kiers et al., 2007; Pérez-Jaramillo et al., 2019; Porter and Sachs, 2020). Seeds that flow through these systems also are often bred for specific traits, such as high yield (i.e., high yield varieties, HYV), and other traits that focus on short-term profit and lead to reduced diversity (Bellon et al., 2017). Furthermore, seeds grown in lab conditions can contribute to biotic and abiotic stress in the field because of the spatial disconnect between where they are bred (centralized location) and where they are grown (wide distribution). Continued use of formal seed systems in a changing climate will thus require more intense breeding cycles (Atlin et al., 2017). However, other models of formal seed systems do exist, in which seed companies such as High Mowing Organic Seeds in Vermont represent an alternative to conventional formal seed systems and specialize in organic and open-pollinated varieties (Helicke, 2015).

While it is true that formal systems predominate in the U.S., informal systems continue to persist in various pockets across the country (Campbell, 2012; Soleri, 2018; Veteto, 2014). Vermont is no exception, as evidenced by the prevalence of seed libraries and seed-saving groups. The Vermont Seed Systems survey showed “robust” informal seed systems in Vermont, such as the Upper Valley Seed Savers (Figure 5-9) (Baxley et al., 2020). Vermont is also home to the High Mowing Organic Seeds company, which is a prime example of a resilient and non-GMO formal seed system relative to industry giants like Monsanto. Furthermore, recent evidence indicates that non-commercial seed growers such as gardeners and seed savers may be maintaining a high degree of crop diversity (Baxley et al., 2020). As such, although public and private research communities often have centered their attention around formal systems (Otieno et al., 2017; Scoones and Thompson, 2011), informal seed systems in Vermont provide a promising agricultural area that, if supported, can provide valuable ecosystem services, bolster food security (Fess et al., 2011; Khoury et al., 2014), and assist in adapting to climate change (Ismail et al., 2013). Also, UVM is planning on saving seeds for backup and recognizes that continued cultivation and use of informal seed systems is an important way to adapt to climate change.

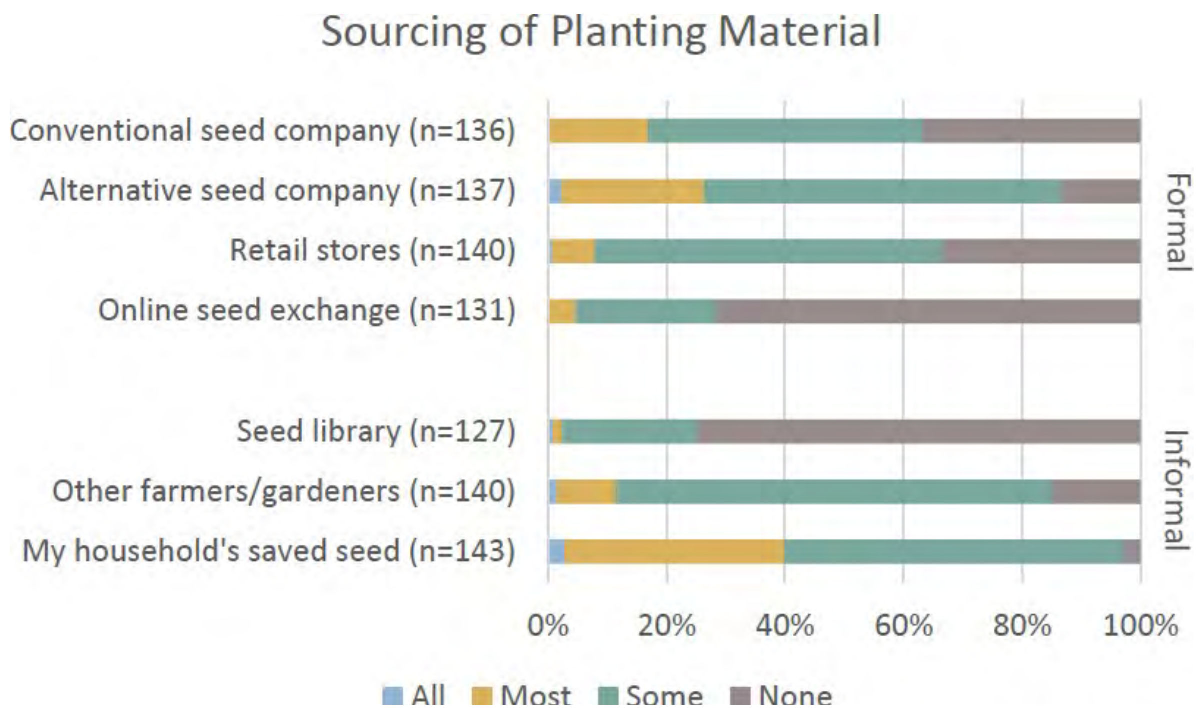


Figure 5-9: Responses to a survey on Vermont seed systems show the distribution of sources of planting materials (Baxley et al., 2020)

Box 5.2: Informal seed systems: A Vermont Case Study (J. Guo, 2020)

The many informal seed networks that exist in Vermont can act as a framework for sustainable, community-based food systems. One example can be found in the Bhutanese-Nepali refugee population that has settled in Chittenden County. In a study of two community garden programs, New Farms for New Americans (NFNA) at the Ethan Allen homestead (n=15) and Winooski Community Gardens (n=15), participants were found to practice sustainable, community-based farming that provided a source of culturally important foods. Although these farmers use both formal and informal seed systems, informal seed systems are an important source for culturally important varieties that are difficult to find within the formal system.

Moreover, informal seed systems help maintain social relationships between family members and friends. Indeed, many NFNA farmers share seeds among each other and can take advantage of greenhouses and their own homes to extend the growing season and grow crops that are not well adapted to Vermont's relatively short growing season. Thus, Bhutanese-Nepali refugees are not only maintaining a valuable cultural and genetic diversity through their production and subsequent seed saving but they are also adapting crops to Vermont and diversifying the gardening landscape of Chittenden County.

There are many examples of how the Bhutanese-Nepali farmers have adapted to relatively Vermont's short growing season. In their native countries, the growing season allows for some varieties of long-growing pumpkins to grow to maturity; while in Vermont they eat the leaves and shoots from such pumpkins throughout the growing season though the gourd may not reach maturity by the time the growing season ends. The community has also experimented with a traditional crop called *tukruke*. One farmer tried it out in Vermont, made the necessary adjustments, and then shared his seeds and knowledge with others; now it is common in the Bhutanese-Nepali plots at both the Ethan Allen and Winooski gardens.

4.5 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

<table>
<tr><td colspan="2">Key message 1: Vermont’s climate is already changing in ways that benefit its agricultural system, including longer growing periods (freeze-free periods lengthened twenty-one days since early 1900s) and milder temperatures (increased annual average temperatures 2°F (1.1°C) since the 1990s), allowing farmers to experiment with new crops or practices not previously viable in Vermont.</td></tr>
<tr><td>Confidence level</td><td>High</td></tr>
<tr><td>Major Uncertainties:</td><td>Degree of year-to-year weather fluctuations from the normal is a global phenomenon and will be a function of GHG mitigation and sequestration.</td></tr>
<tr><td>References</td><td>Trends in long-term Vermont-specific data. Climate Change in Vermont chapter and Wolfe et al. (2018)</td></tr>
</table>

<table>
<tr><td colspan="2">Key message 2: The changing climate causes agricultural setbacks, such as negative impacts on fruit-bearing species like apple trees that require a sufficient over-wintering period for success in the next growing season. The maple syrup industry is also at risk due to variations in winter temperatures.</td></tr>
<tr><td>Confidence level</td><td>High</td></tr>
<tr><td>Major uncertainties:</td><td>Degree of year-to-year weather fluctuations from the normal is a global phenomenon and will be a function of GHG mitigation and sequestration.</td></tr>
<tr><td>References</td><td>Trends in long-term Vermont-specific data. Climate Change in Vermont chapter and Wolfe et al. (2018)</td></tr>
</table>

<table>
<tr><td colspan="2">Key message 3: Climate models predict tougher growing conditions due to greater variability in temperature and precipitation, including heavy precipitation and dry spells.</td></tr>
<tr><td>Confidence level</td><td>High</td></tr>
<tr><td>Major uncertainties:</td><td>Degree of year-to-year weather fluctuations from the normal is a global phenomenon and will be a function of GHG mitigation and sequestration.</td></tr>
<tr><td>References</td><td>Trends in long-term Vermont- specific data. Climate Change in Vermont chapter and Wolfe et al. (2018)</td></tr>
</table>

<table>
<tr><td colspan="2">Key message 4: Vermont’s average annual precipitation has increased 6.7 inches since the 1960s. Summer precipitation has increased most (additional 2.6 inches since 1960s) and is characterized by more heavy precipitation events (defined as more than one inch of precipitation in one day) (additional 1.0 day/year), although spring precipitation has also increased notably (additional 2.11 inches/year since 1960s, and 0.8 days/year with heavy precipitation). Spring precipitation accumulates in the soil and can make farm operations difficult. While precipitation during the growing season is trending upward, precipitation falls in fewer, more extreme events and is coupled with longer periods of no rain at times when crop water requirements are still high; thus, irrigation may become increasingly important.</td></tr>
<tr><td>Confidence level</td><td>Medium</td></tr>
<tr><td>Major uncertainties:</td><td>Degree of year-to-year weather fluctuations from the normal is a global phenomenon and will be a function of GHG mitigation and sequestration.</td></tr>
<tr><td>References</td><td>Trends in worldwide atmospheric data. Wolfe et al. (2018)</td></tr>
</table>

Key message 5: At the Earth's surface, increasing concentrations of carbon dioxide may benefit yields in crops that utilize the C3 photosynthetic pathway (i.e., many of Vermont's forages) if conditions are otherwise ideal. Conversely, an increase in surface-level ozone concentrations may reduce crop productivity.	
Confidence level	Medium
Major uncertainties:	Degree of year-to-year weather fluctuations from the normal is a global phenomenon and will be a function of GHG mitigation and sequestration.
References	Trends in worldwide and Vermont-specific data and climate models. Wolfe et al. (2018)

Key message 6: Extreme events are expected to increase, which will result in more periods of flooding and drought and crop damages or failures. Stormwater and irrigation infrastructure will be crucial in mitigating these effects.	
Confidence level	Medium
Major uncertainties:	Degree of year-to-year weather fluctuations from the normal is a global phenomenon and will be a function of GHG mitigation and sequestration.
References	Trends in worldwide and Vermont-specific data and climate models. Wolfe et al. (2018)

Key message 7: Agriculture and food systems may play an important role in mitigating climate change, if mitigation provides financial opportunities, are distributed fairly, and are implemented accurately with careful monitoring, reporting and verification. Urban and suburban areas in Vermont have the potential to improve adaptation and mitigation of climate change by growing food closer to where it is consumed.	
Confidence level	Medium
Major uncertainties:	Degree of year-to-year weather fluctuations from the normal is a global phenomenon and will be a function of GHG mitigation and sequestration. Public awareness and action are a function of perceived urgency to address climate related issues.
References	Trends in worldwide and Vermont-specific data and climate models. Vermont farm research and surveys. Birthisel et al. (2020); Willard et al. (2020); Wolfe et al. (2018)

4.6 REFERENCES

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5 ENERGY

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5.1 KEY MESSAGES

1. Vermont drivers have the highest average miles traveled per capita in the Northeast United States. Transportation is the largest source of greenhouse gas emissions in Vermont. Thermal energy use is a close second to the largest source of greenhouse gas emissions in Vermont, and the largest use of energy. Reducing energy use in these sectors by choosing more efficient vehicles, selecting heat sources with less emissions, and weatherizing homes will help Vermont meet its energy goals.
2. The electricity in Vermont has the lowest carbon intensity in the country. Electrifying transportation and thermal energy use will significantly reduce Vermont's carbon footprint.
3. In the short term, there is extra power line capacity to serve significantly more load in Vermont; however, some areas of Vermont have limited capacity to support further renewable energy generation. Areas where there is limited generation hosting capacity could be prioritized to shift local energy use to electricity to reduce congestion on local transmission lines. The priority in areas with extra generation hosting capacity can be two-fold: building new renewable generation and electrifying local energy use.
4. The storms that cause the most frequent power outages are expected to become more intense in the future, increasing the frequency of power outages, particularly in winter. Vermont can increase its energy resilience with distributed solar and storage, secondary heating systems (e.g., wood), and community buildings with resilient heating solutions.

5.2 BACKGROUND/OVERVIEW

Climate change and energy use are interdependent. The release of greenhouse gases (GHGs) into the atmosphere from the use of fossil fuels drives climate change (see Climate Change in Vermont chapter), and conversely the changing climate heavily impacts energy infrastructure by increasing storm intensities and weather variability. Changing climate patterns—such as the warming arctic leading to lower wind speeds and increasing temperatures—decrease wind and solar production efficiency (Solaun and Cerdá, 2019), decrease the capacity of electric power lines, and increase the need for cooling in thermal power plants. More frequent periods of drought induced by climate change can impact water supplies available for hydro generation and thermal generator cooling needs (Zhou et al., 2020). Climate change also impacts energy use in varying ways, increasing the cooling needs in the summer, while creating large variability in winter heating, making needs harder to predict beyond short-term temperature estimates.

Historical decisions made within the energy sector have had a negative impact on the environment and human health. Now, balancing the immediate needs of communities (thermal, transportation, etc.) with the need to address climate change is a challenge faced across sectors. As shown in Figure 6-1, energy use (which includes thermal, transportation, and electricity) was responsible for 76% of Vermont's GHG emissions in 2018. Those emissions are not yet decreasing at the rate needed to reach Vermont's climate goals. Increases in the use of low/no greenhouse emission energy sources for transportation and thermal energy uses and improvements in the efficiency of transportation and thermal energy uses have the best potential to greatly reduce greenhouse gas emissions in the state.

One way to reduce total emissions is to look across sectors for wasted energy, so that wasted energy in one sector that can be captured for use in different sectors. Consider, for example, Vermont's "cow power" program, which reduces methane production from manure by capturing it and burning it as a biofuel to produce electricity (Levine 2013). While CO_2 is produced when methane is burned, methane has about eight times the global warming potential of CO_2; additionally, GHG emissions are offset by producing usable energy that would otherwise have been generated another way. This program reduces net GHG emissions by using emissions from the agriculture sector for use in the electricity or thermal sectors.

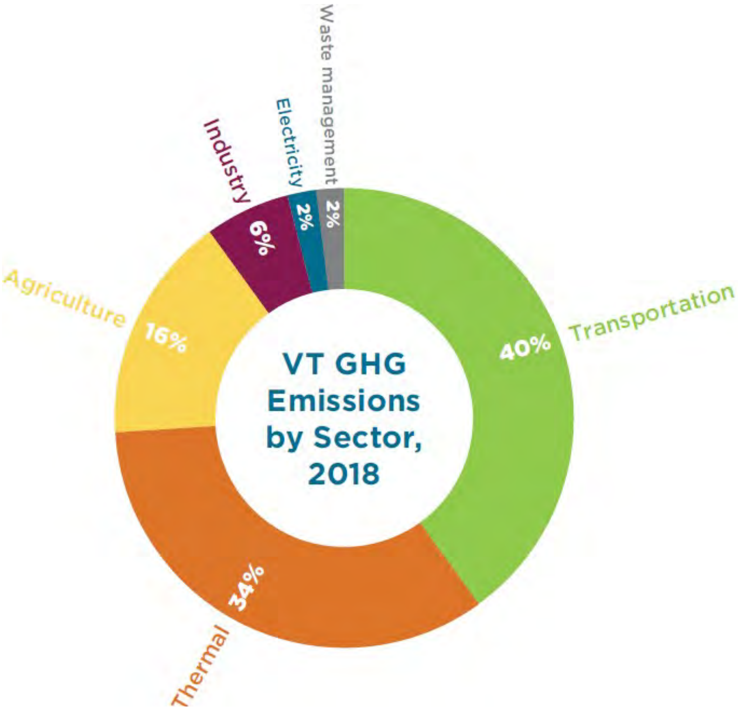


Figure 6-1: Percent of GHG emissions by sector in 2018 in Vermont (Duval et al., 2021).

It should be noted that there are many ways to look at energy use, and they each have nuances about what they include. The data in Figure 6-1 show the impact of energy used within the state, but the figure does not show energy inputs and exports. Thus, the energy used to produce and transport items that are produced elsewhere but consumed in Vermont is not included here. This missing carbon is often called *embedded* or *imported carbon*. While it is difficult to say who is responsible for these emissions, it is important to account for them and to minimize them. Since climate change is a global challenge, exporting carbon emissions to other places does not solve the problem.

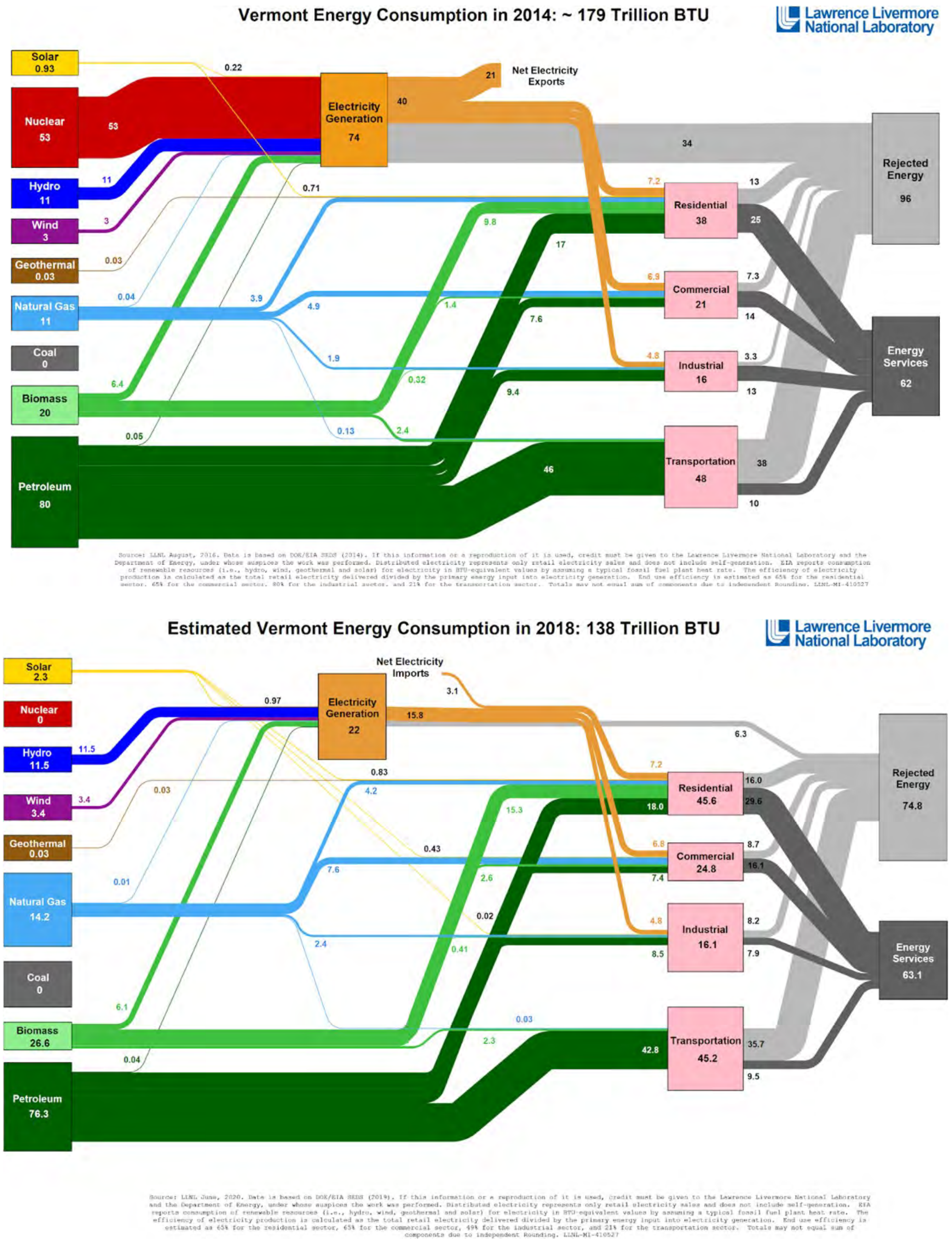
The Energy Action Network produces an annual progress report that analyzes energy data for the state of Vermont and models pathways to the state's energy goals. This chapter draws data from this most recent report (Duval et al., 2021) to describe the state of energy within Vermont. This chapter also provides background information about how energy systems work, describes the inherent difficulties of estimating GHG emissions, and suggests data that could be helpful in providing a clearer picture of GHG emissions and energy use in Vermont.

The remainder of the chapter is laid out as follows. Section 6.3 describes energy uses in Vermont, followed by a high-level overview of the energy planning process and equity of energy use in section 6.4. Finally, section 6.5 describes how expected climate change impacts are likely to effect energy infrastructure and offers potential pathways toward resilient energy systems.

5.3 ENERGY USE IN VERMONT

Delivering the energy whenever someone decides to turn on a lightbulb, fill a car’s gas tank or battery, and turn up the heat takes enormous preparation, large networks of interdependent infrastructure, and constant monitoring. The energy in each of these examples is considered *site energy*, as opposed to *primary or source energy.* Primary or source energy includes energy losses during the transportation and conversion (as is the case with electricity) of the energy. This section gives an overview of the use of energy within Vermont, covering the primary sources of energy, the flow and conversion of that energy into usable forms, and the end uses of energy.

Figure 6-2 shows the flow chart for Vermont’s energy use in 2014 (top) and 2018 (bottom), capturing the whole system from the sources of energy to the end uses. In light gray is the *rejected energy*, which is energy available in the resource (included in the source energy) but not captured in the conversion to usable energy. The dark grey bands depict *energy services*, which include all the energy that was used for the intended purpose, be that heating a home, powering lights, or accelerating a car. The estimated rejected energy— energy available in the resource but not captured into usable energy—is accounted for. The conversion into electricity and the flow from the source to different users is shown through the charts’ many connections. It is worth noting that accounting for energy use in Vermont is inexact, since it is difficult to accurately model the primary energy sources of electricity that are imported and the GHG emissions associated with manufacturing, transportation of products sold within the state, and other embedded and imported emissions (Davis & Caldeira, 2010).



Source: LLNL August, 2016. Data is based on DOE/EIA SEDS (2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Source: LLNL June, 2020. Data is based on DOE/EIA SEDS (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 49% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Figure 6-2: The 2014 energy flow chart for Vermont, (LLNL 2016).; Bottom: The 2018 energy flow chart for Vermont (LLNL, 2020)

Note: Neither flow chart includes behind-the-meter solar electricity generation. Both include assumed efficiencies to measure wasted (rejected) energy. Vermont Yankee closed in December of 2014 (U.S. Nuclear Regulatory Commission 2021).

5.3.1 Primary Energy Sources

Primary energy sources include not only energy that is used in the state of Vermont, but also the energy that is lost in the process of mining, transporting, converting, and using that energy. Sometimes called *source energy*, primary energy sources come straight from mines, fracking wells, dams, solar radiance, etc. The source energy attributed to Vermont in 2014 and 2018 is displayed in Figure 6-3.

The sources of energy that were used in Vermont in 2014 include solar, nuclear, hydro, wind, geothermal, natural gas, biomass, and petroleum. In 2014 Vermont Yankee was closed for good, and the difference between the top and bottom images in Figure 6-2 illustrates the large effect of the closure in the reduction in wasted energy, labeled rejected energy in the flow chart, and the switch from 21 BTU equivalent electricity exports to 3.1 BTU equivalent electricity imports.

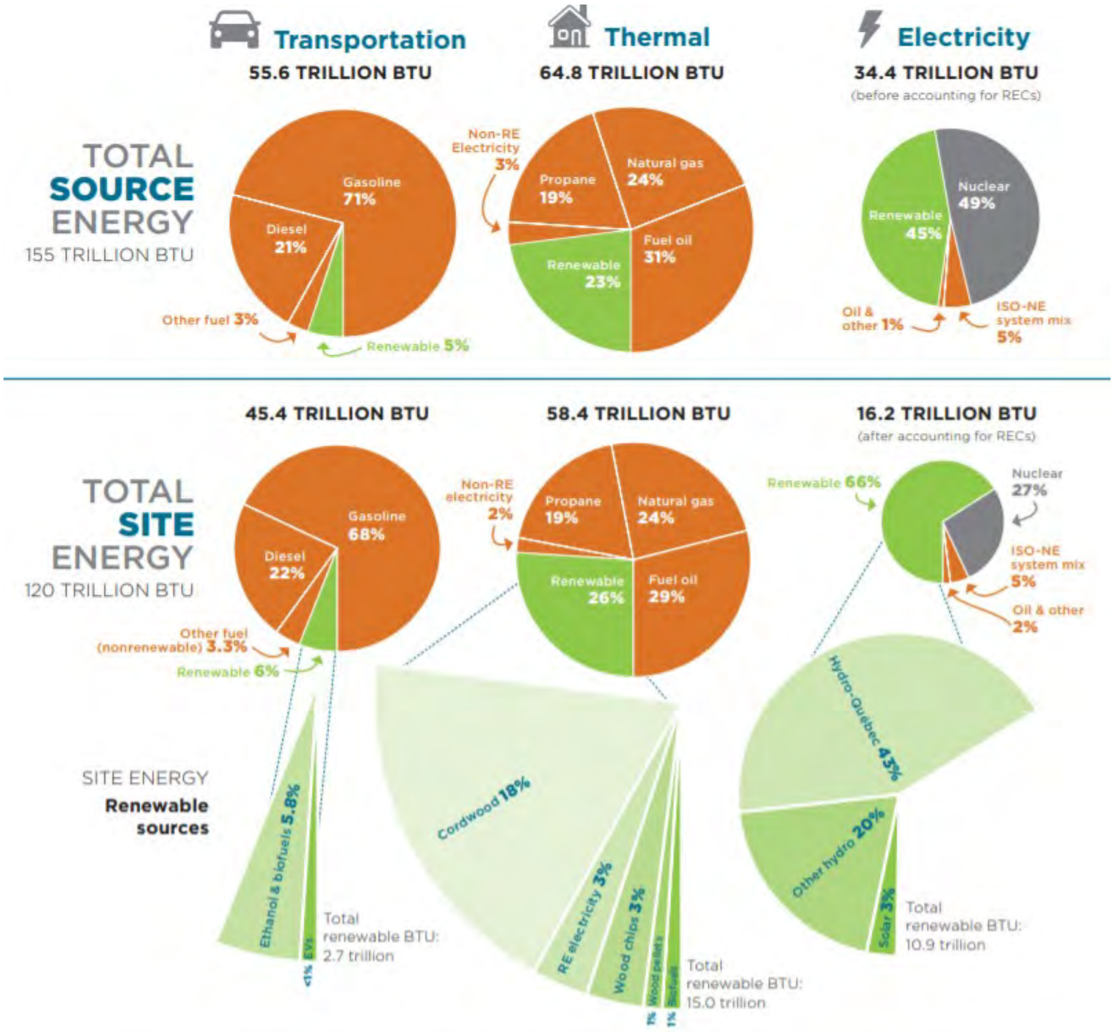
Vermont's sources of energy in 2018 included solar, hydro, wind, geothermal, natural gas, biomass, and petroleum, in addition to energy sources imported from other states and Canada to serve Vermont's electric load. The Water Resources chapter of this report discusses changes in water usage from the shutdown of Vermont Yankee. Many state policies have interacted to lead to the transition seen in the energy generation in the state, this is discussed further later in this chapter.

Not only does the state import electricity, but most of the energy that is used within the state is imported. Source energy can be broken down into sectors, as shown in the top row of the chart in Figure 6-3. Transportation and heating account for most of the energy use in the state and the lion's share of the nonrenewable energy use in the state. Also shown in Figure 6-3 is the site energy—e.g., the gas pumped into a car or the electricity used by an electric kettle to boil water—which still includes some of the rejected energy shown in Figure 6-2. There is a significant amount of waste heat produced by internal combustion engine vehicles, and even an electric kettle wastes some electricity into waste heat. However, to become categorized as site energy, the primary source energy must first arrive in the expected form on site.

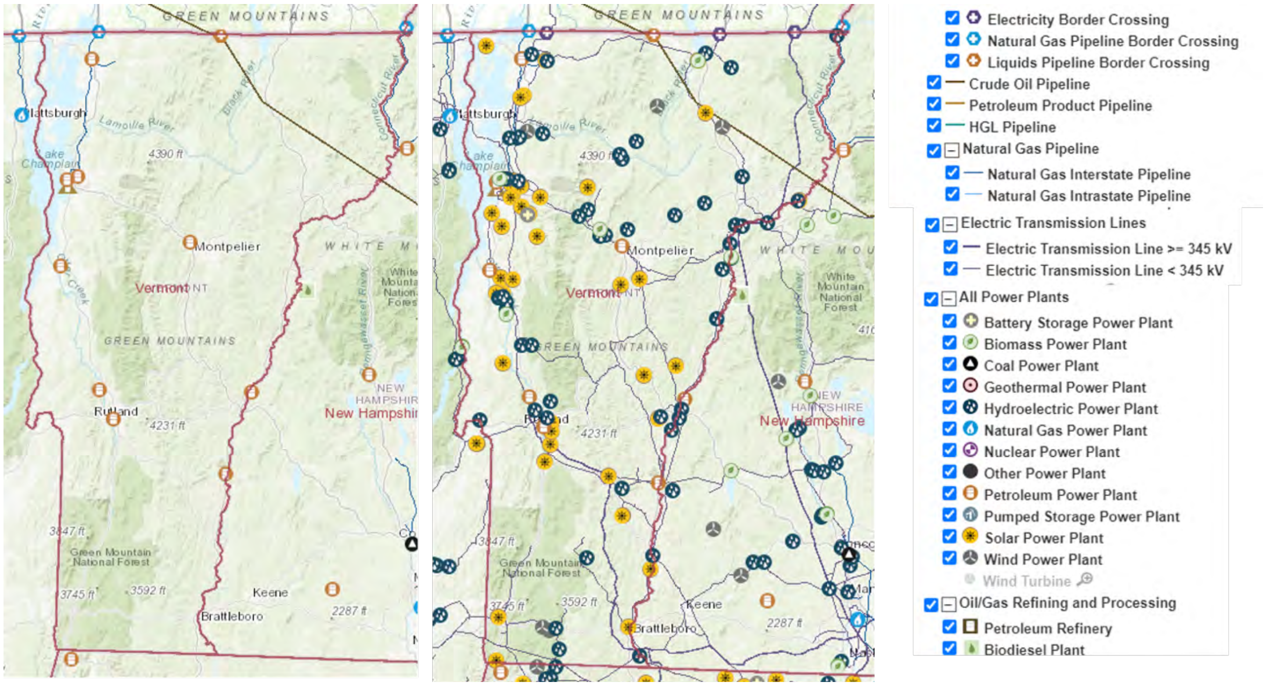
5.3.2 Energy Flow and Conversion

Whether energy comes from a mine, a dam, or a wind/solar farm, it must be both converted and transported, sometimes multiple times, in order to arrive in a useful form at its end-use location. The process of transporting energy can occur before or after converting. Petroleum products must go through a facility to separate the components; natural gas is often transported through pipelines. Various energy sources are converted into electricity and transported in that form through the transmission network. Vermont's electric network is a small part of the Eastern interconnect, which covers the continental U.S. east of the Mississippi River. There are losses during the transportation and conversion of energy, and there are limitations on the capacity of pipelines to store and transfer petroleum or natural gas and of electric grid wires to provide power.

Vermont is unique in that almost all its energy flows from sources outside the state. There are no fossil fuel mines in the state, so all petroleum products—i.e., gasoline, fuel oil, and natural gas—used within the state are imported. The infrastructure in the state is shown in Figure 6-4. In 2014, the state was exporting electricity to other states for 73% of the hours in the year, but in 2015, Vermont was importing electricity for 84% of the hours in the year (VELCO, 2021). In other words, the state switched from exporting power during the majority of the year to importing power during the majority of the year. The wood harvested for thermal energy each year is about 50% of the new growth in the state (Burlington Electric Department 2019).



Sources: Energy Information Administration, Efficiency Vermont, Vermont Department of Public Service, Vermont Agency of Natural Resources, and Energy Action Network.



Note: The left panel shows the natural gas and petroleum pipelines coming into Vermont and natural gas and petroleum generators, the middle panel shows the pipelines, electric grid, all generators, and refineries in the state and surrounding area.

5.3.2.1 Electricity

Standard practice in the energy industry is to design systems so that energy supply is always ready to meet demand. This rule applies for most energy supply systems, but it is especially relevant to electric power, where the stability of the network is dependent on supply always matching the combination of demand and the losses. This is key to understanding the challenges needed to overcome to increasingly variable resources. In addition, the push towards using variable resource technologies like wind and solar to supply electric power is occurring within the context of increasing constraints associated with transmitting power into (and not out of) rural areas. The power grid was designed to serve dispersed demand from a few central power plants.

Currently, electricity is still mainly produced from converting forms of stored energy when needed. The exception is variable resource generators (e.g., wind and solar), which are only capable of converting the energy into electricity while that resource is available, i.e., the wind is blowing where wind generators are located, the sun is shining on solar panels, and the water is flowing in rivers with run-of-river hydro generation. The forms of stored energy used to generate electricity when there is electric demand include hydro (with large dams), biomass, natural gas, and petroleum. There are losses in the transmission of electricity from the generators to the end users. However, those losses are small compared with conversion losses that result in waste heat. If not considering embedded emissions, Vermont's electricity is currently responsible for the lowest GHG emissions of any United States state's electricity profile (Duval et al., 2021). It is worth noting that any GHG emissions that occurred from energy sources designated renewable are not considered.

5.3.2.2 Natural Gas

Vermont Gas is the only natural gas supplier in the state. It imports gas from Canada to Chittenden, Franklin, and Addison counties. Natural gas is supplied through underground pipelines to personal residences and businesses. Natural gas mainly supports the thermal sector. Energy from natural gas that has been converted into electricity (outside the state) is imported with the regional electric grid system mix and used to supply the state's electricity demand. The impact of using natural gas to heat depends on the efficiency of the heater and the weatherization of the building.

5.3.2.3 Other Transported Energy

Wood, oil, propane, gasoline, diesel, and biofuels are all transported by pipelines, cargo ships, trains, and vehicles to homes and businesses before being converted from chemically stored energy into usable and waste heat energy used for our thermal, transportation, and electricity needs. Vermont only has one petroleum pipeline coming through the northeast corner of the state (Figure 6-4), so our fuel comes from ports on Lake Champlain, cargo trains, and trucks into the state.

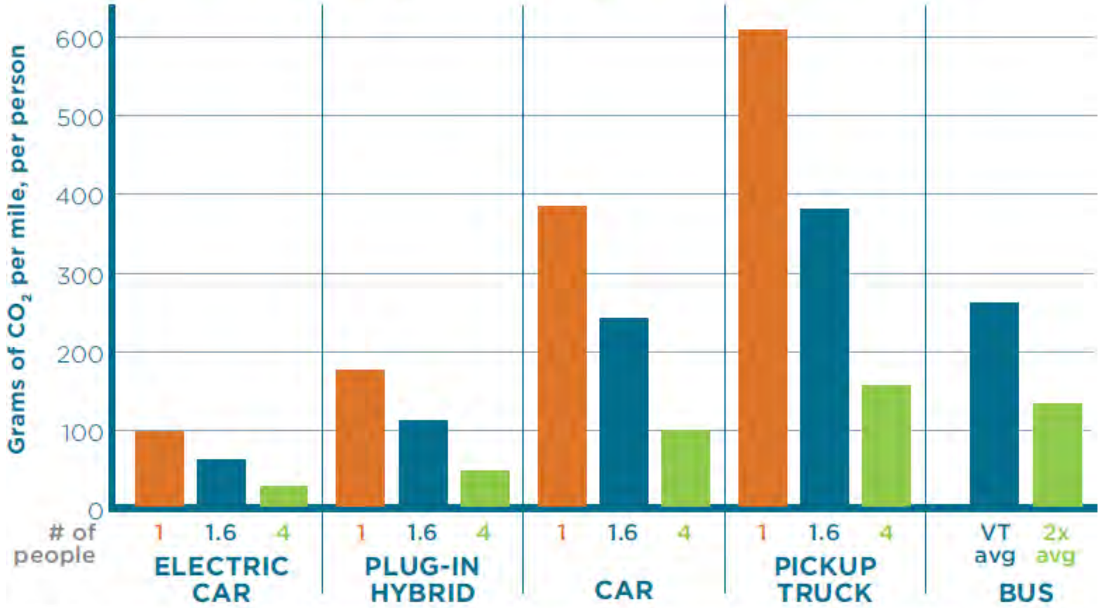
5.3.3 End Uses and Impacts

As seen in Figure 6-3, thermal uses the most energy in Vermont, followed closely by transportation. However, transportation is responsible for 40% of the state's GHG emissions, while thermal is responsible for 34% of the emissions. There is potential for large increases in the efficiency of energy use for thermal and transportation needs, and yet GHG emissions from these sectors are not decreasing. One example of why this may be the case is the size of vehicles used in the state: despite improvements in vehicle efficiency technologies, the average efficiency of Vermont's vehicle fleet is largely unchanged (VT Agency of Natural Resources, 2021). A second priority of the state continues to be home and building weatherization, which the state incentivizes. There is potential for scaling these incentives to increase the rate of improving thermal energy efficiency. Boosts in energy efficiency, in general, reduce the amount of energy needed to fulfill the energy needs of Vermont's population. Electric cars are far more efficient than the gas equivalents, and home weatherization and transitions to more efficient heating options are both ways to decrease the energy use for thermal needs.

5.3.3.1 Transportation

Transportation is the largest producer of GHG emissions in Vermont, producing about 40% of the state's emissions. It's also the second largest use of energy, after thermal. Vermonter's travel on average 11,773 miles each year, which is higher than the average in surrounding states and the United States as a whole (Duval et al., 2021). Shown below in Figure 6-5, is the CO_2 production per mile by various vehicle types considering the number of passengers. As public transportation shifts to using electric vehicles, the “bus” column will show far fewer emissions.

Emissions per passenger by vehicle



Source: Union of Concerned Scientists, 2021, How Clean is Your Vehicle tool; Argonne National Laboratory, 2021, GREET model; VTrans, 2021, FY20 Public Transit Route Performance Report. Note: 1.6 passengers is the national average in a car trip.

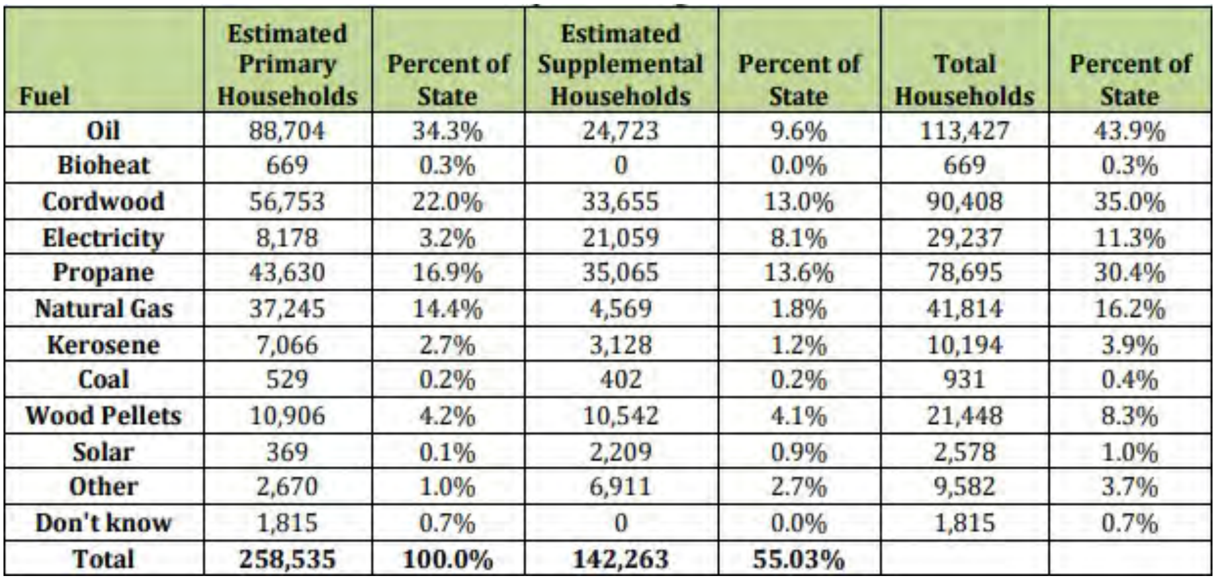
Manufacturing a mid-sized internal combustion engine car produces approximately 5.6 tCO$_2$e, and a similarly sized electric vehicle produces 8.8 tCO$_2$e (Low Carbon Vehicle Partnership, 2021). The average lifecycle of a car in Vermont is around ten years (WJXT News 4 JAX, 2019). Together, these figures show that the annual CO$_2$ emissions produced by an electric vehicle (2.2 tCO$_2$e) were less than half of the emissions produced by an internal combustion car produces (5.5 tCO$_2$e). Even considering production and the first year of driving, the electric vehicle produces 10.1 tCO$_2$e, while the internal combustion car produces 10.5 tCO$_2$e. The incentives to switch to electric vehicles are making it financially competitive when considering the lower cost of fuel. In addition, the emissions from operating electric cars are lower to operate the electric vehicle, so much so that the additional emissions that go into producing electric vehicles are offset within the first year. Behavior changes—driving less, telecommuting, carpooling, utilizing public transit, and community restructuring to support greater walkability—are also important ways to reduce the impact of transportation on the state's GHG emissions.

5.3.3.2 Heating

Energy used for heating is the largest use of energy in the state of Vermont. The two most common heat sources in the state are fuel oil and natural gas, as shown in Figure 6-3. Weatherizing houses is extremely important to making comfortable homes that can be heated efficiently, especially considering the state's housing stock is some of the oldest in the country. The commercial sector uses even fewer renewable sources than the generalized state heating sources (Duval et al. 2021). Table 6-1 shows the fuel used both as the primary and supplemental forms of heating in Vermont for 2018-2019. The estimated number of households using each fuel source comes from surveys performed by the Vermont Department of Forests, Parks, and Recreation and the University of New Hampshire Survey Center (VT Department of Forests, Parks and Recreation, 2019). Note that the sum of the final column is more than 100% because it represents the percent of the state using both primary or secondary heat sources, and so many households are counted twice.

Figure 6-6 shows which fuel used for heating in Vermont in the years in which data was collected between 1986 and 2019. Oil and wood remain the most prevalent fuels, although the fuels used for heating have diversified in approximately the last decade. Table 6-1 and Figure 6-6 show that residential heating sources and commercial and industrial heating sources continue to rely heavily on fossil fuels (Duval et al., 2021).

Table 6-1: Fuels used for space heating in Vermont 2018–2019. Source: the 2019 Vermont Residential Fuel Assessment.



Fuel	Estimated Primary Households	Percent of State	Estimated Supplemental Households	Percent of State	Total Households	Percent of State
Oil	88,704	34.3%	24,723	9.6%	113,427	43.9%
Bioheat	669	0.3%	0	0.0%	669	0.3%
Cordwood	56,753	22.0%	33,655	13.0%	90,408	35.0%
Electricity	8,178	3.2%	21,059	8.1%	29,237	11.3%
Propane	43,630	16.9%	35,065	13.6%	78,695	30.4%
Natural Gas	37,245	14.4%	4,569	1.8%	41,814	16.2%
Kerosene	7,066	2.7%	3,128	1.2%	10,194	3.9%
Coal	529	0.2%	402	0.2%	931	0.4%
Wood Pellets	10,906	4.2%	10,542	4.1%	21,448	8.3%
Solar	369	0.1%	2,209	0.9%	2,578	1.0%
Other	2,670	1.0%	6,911	2.7%	9,582	3.7%
Don't know	1,815	0.7%	0	0.0%	1,815	0.7%
Total	**258,535**	**100.0%**	**142,263**	**55.03%**		

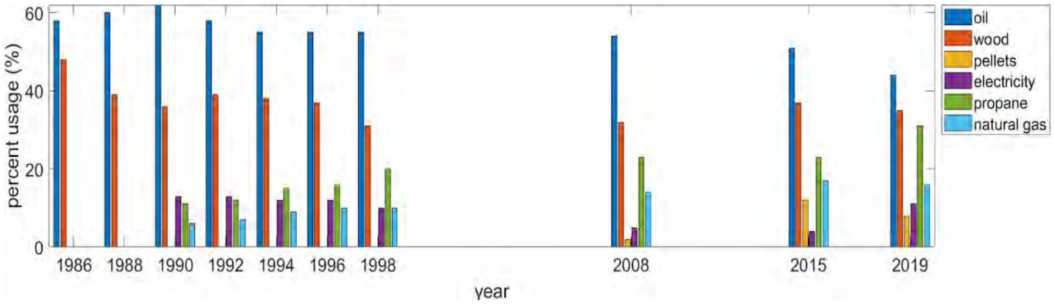


Figure 6-6: Vermont's residential heating sources. Data from the 2019 Vermont Residential Fuel Assessment and VT Department of Forests, Parks and Recreation (2019).

5.3.3.3 Electricity

Vermont's electricity is the cleanest in the country, based on estimates that it contributes 2% of the state's GHG emissions. Electricity supplies 13.8% of the site energy and 22.1% of the source energy to the state (Duval et al., 2021). There is no carbon accounting for hydropower, solar, and wind, although this does include the estimated contribution from the imported electricity attributed to fossil fuel sources. There are carbon emissions from the flooding process involved in creating the dams used in hydropower, and Hydro-Québec does produce carbon from this process (VT Agency of Natural Resources, 2021). Whether Canada should be quantifying the GHGs produced by Hydro-Québec on a land use basis or an electricity production basis is being debated (Gokee, 2020). There are also carbon emissions associated with the manufacturing, transportation, and installation of solar and wind resources. Life-cycle assessments on renewable resources for potential generation sites are needed to optimize both where resources are placed and what type of generation resources will lead to minimum net greenhouse gas emissions. Including diverse information on the potential impacts is also important in siting renewable resources to ensure that other important ecosystem services, such as diversity and water storage, are not accidentally compromised.

5.4 ENERGY PLANNING AND EQUITY

Energy policy can protect vulnerable communities and impact energy sources and energy use in Vermont. For example, Vermont's electricity sources are estimated to have the lowest GHG emissions of any state in the United States (Duval et al., 2021), and the biggest changes in emissions from the electricity sector occurred after policies strongly incentivized the development of renewable energy.

5.4.1 State Level Energy Planning

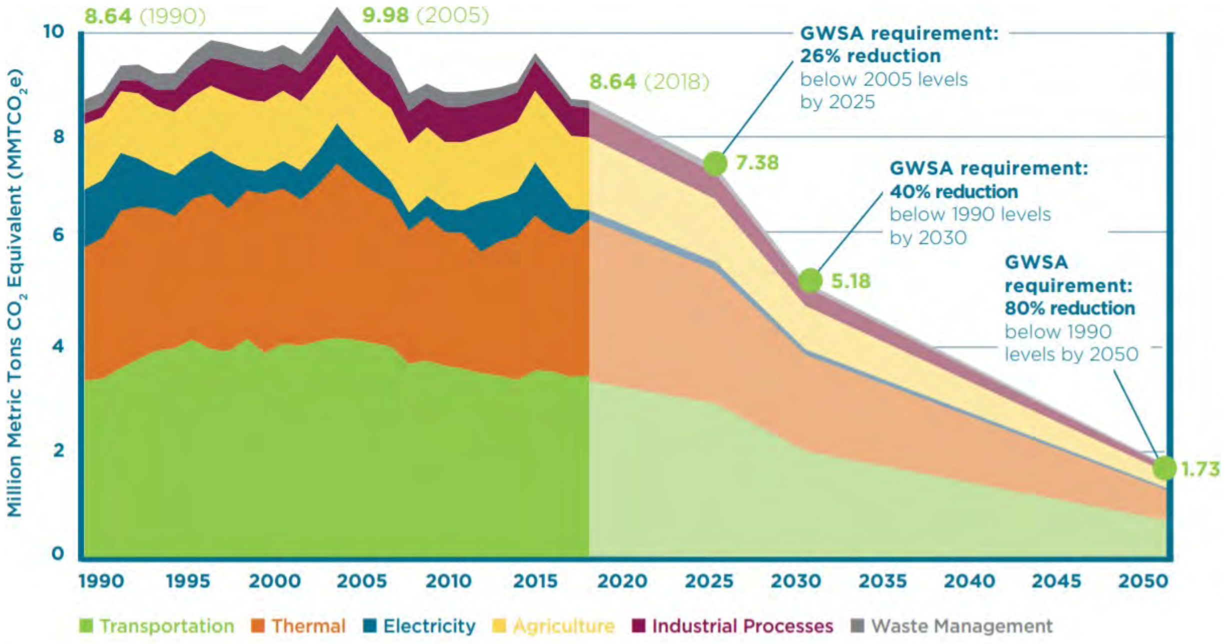
There are many players and actors in energy planning. In the electricity sector, actors include the independent system operator for New England, ISO-NE; the transmission operators and planners in Vermont, VELCO: the Vermont Department of Public Service; and the Vermont Public Utility Commission (PUC). Further, actions need to be approved at either the federal or state level, depending on the type of action. At the federal level, the Federal Energy Reliability Council makes the rulebook for interstate wholesale power sales. At the regional level, ISO-NE must approve transmission planning. At the state level, the Vermont PUC must approve retail rate changes, siting new resources, and renewable planning (Vermont Business Magazine, 2021; VT Department of Public Service, 2021).

In large part due to the work of Efficiency Vermont, electric energy consumption in Vermont is relatively stagnant, even decreasing slightly from 2014 to 2018, as shown in the charts in Figure 6-2. Vermont's electricity sector has shown capacity to react to new policies. Several state policies—including the Sustainably Priced Energy for Economic Development (SPEED) program, net metering, standard offer, and the renewable energy standard—have helped the electricity sector transition to a more renewable energy portfolio (VT Department of Public Service, 2021). Since new transmission and distribution (T&D) investments are expensive and time-consuming projects that impact local landscapes, stakeholders in Vermont minimize the amount of new T&D construction. The slow increase of electric rates in Vermont can be seen in these decisions as well, because T&D investments can result in large increases to customer electric rates. Yet, enabling a rapid transition to renewable energy will require that new renewable energy projects be rapidly approved and connected to the grid where the power is needed. There are many challenges in that process, including land use disputes, choosing plant locations that aren't sequestering carbon, placing energy resources in an equitable way, and placing and sizing resources where the grid has capacity for the power.

5.4.1.1 Global Warming Solutions Act

The Global Warming Solutions Act (GWSA) is a state bill that adds enforceable targets to Vermont's goal of reducing carbon emissions. The bill also requires that the pathways utilized to get to the required emission reductions reduce energy burden. Energy burden is related to the amount of money a person spends on energy resources compared with their income; a high energy burden would occur if a large percent of a household's income goes towards the energy use of the household. Figure 6-7 shows carbon emissions by sector and a potential pathway to meet each of the required GHG reduction benchmarks in the act. This policy makes the state accountable for achieving these goals. The figure shows how transportation, thermal energy, electricity, agriculture, industrial processes, and waste management have contributed to the GHG emissions of the state over time and how they must reduce emissions to reach GWSA targets. It is clear how the electricity sector has reduced emissions, with support from the state's policies. Similar reductions have not been seen in transportation or thermal energy use.

Since transportation is the leading producer of GHG emissions in the state, shifting the use of fossil fuels to electricity produced with the current mix of generation types will significantly decrease GHG production from the transportation sector and the state. Weatherizing to increase buildings' thermal efficiency and electrifying home and building heat sources are other large components of the emissions reductions pathways required by the GWSA and shown in Figure 6-7.

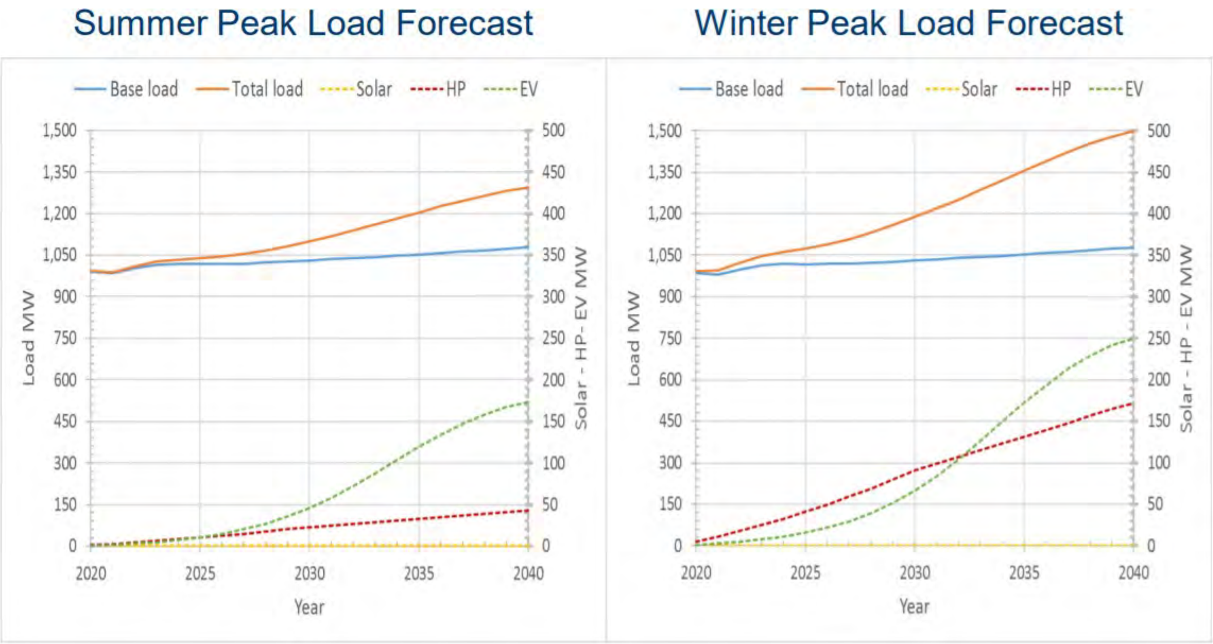


Source: Vermont Agency of Natural Resources, Vermont GHG Emissions Inventory and Forecast (1990-2017), 2021.

Figure 6-7: Historical sectoral CO_2 emissions and proposed future emissions that align with the Global Warming Solutions Act in Vermont (Duval et al., 2021)

5.4.1.2 Electricity Demand Forecasts

Plans to electrify energy use of the thermal and transportation sectors could significantly increase electricity use in the state. Since electric grids have been planned around certain levels of electricity use, it is especially important to plan for a potentially sudden increase in electricity use in the state. Figure 6-8 shows the summer and winter peak forecasts from VELCO's long-range transmission plan. These forecasts are based on a scenario where peaks are expected to be higher than 90% of the possible load scenarios under extreme weather conditions (VELCO, 2021). As shown in the figure, the largest increase in demand over the next twenty years is expected to be the charging of electric vehicles and the use of heat pumps. A huge part of the pathway to the state’s commitment to reduce GHG emissions will be achieved through this increase in electricity use and decrease in fossil fuel consumption. Another recent development contributing to electrification is the designation of three of Vermont’s highways as alternative fuel corridors. This illustrates the state’s commitment to transitioning the vehicle fleet to electric vehicles (Vermont Business Magazine, 2021). Roadways designated as “corridor ready” will offer sufficient access to charging stations to support electric vehicle travel. This promotion of the Vermont highway system may further increase electric load, as tourists with electric vehicles may prioritize these routes for travel between cities in Vermont and outside, such as, Boston, Albany, and Montreal.


Summer Peak Load Forecast

Winter Peak Load Forecast

Figure 6-8: Summer (left) and winter (right) peak forecasts for the electricity load in Vermont in units of power, megawatts (MW)

Note: Base load is in blue. Total load including solar, heat pumps, and electric vehicles is shown in orange over the next twenty years. The left axis is the reference for the solid lines and the dashed lines correspond to the right axis for both figures (VELCO, 2021).

5.4.1.3 Land Use Changes

Land use is a complex issue that has implications beyond each parcel of land. Some land provides services outside its boundaries, such as clean water from the mountains, local food grown on and harvested from farms, and beautiful outdoor spaces and carbon sequestration from forests. Depending on the management of land and changes in the uses of land, these services can be compromised or developed. For example, as a forest shifts to developed land, many ecosystem services are compromised. Or as a capped landfill changes its land use to electricity production with the installation of solar energy resources, an energy service of that land is developed. Increasing renewable energy generation in the state will result in significant land use change across the state. However, with the state's low population density, currently less than 1% of the state's land use would need to change to supply the state's electricity usage with renewable generators (Thomas and Racherla, 2020). Of course, that is not to say there won't be disputes over land use in the transition to renewable energy (Davis, 2015). Careful planning will be required to ensure an equitable and efficient placement of resources.

Converting land can be controversial, and there are carbon sequestration benefits for some land that could be lost if converted to electricity production, for example, when removing a forest to put in solar panels involves lost carbon sequestration from the trees. Chinnery (2021) estimates that this scenario may lead to the emission of 11.6 tCO_2e; however, Chinnery (2021) also calculates that that panel is expected to produce emission-free electricity for many years, offsetting GHG emissions from where that electricity would be produced otherwise. The same study found that the GHG emissions cost of cutting down one tree and installing a solar panel are about an order of magnitude less (10 times less) than the expected emissions offset by the electricity produced by the panel (Chinnery, 2021). On one hand, more than one panel could be installed by removing the shade from a whole tree, creating a more favorable case for installing the energy resource. On the other hand, with the state's relatively low carbon electricity profile, the case in Vermont would likely favor the tree more than the estimation calculated in Chinnery (2021). It is also important to remember the current land use and the cost of changing land use in siting decisions. For example, building roads where there were none to install energy resources comes with a cost of carbon emissions. While cutting down a forest and installing solar panels leads to fewer carbon emissions per KW than running a coal plant, that comparison is only applicable when the electricity produced by the array of solar panels offsets electricity produced by a coal plant (Turney and Fthenakis, 2011). Forests provide many ecosystem services, not only carbon sequestration, and they are a huge part of Vermont's identity (as is discussed in far more detail in the Climate Change in Forests chapter). Thus, prioritizing non-forested land for renewable electricity generation placement is preferred. To ease some of the anticipated pains related to the transition to renewable energy, there is potential to combine uses to best serve the communities needs where infrastructure is added. For example, combining pollinator habitat with solar and combining sheep grazing with solar are both being practiced with good success in the state.

Several factors are important to consider when siting new wind and solar generation, including energy production per unit land, land cost, land use change, and T&D capacity. The electric grid in Vermont has very limited capacity to support larger power flows out of certain areas in the state (McCallum, 2021; VELCO, 2021). As illustrated in Figure 6-9, this is especially true along Vermont's northern border due to high renewable capacity already installed, incoming power from Canada, low capacity to transmit additional power out of the region, and low demand in this area. The potential to maximize energy production over the year is not equal in of all regions of the state. Figure 6-10 shows several estimates from a study on how to meet Vermont's goals to meet 100% of the electricity demand with renewables in 2050 (Thomas and Racherla, 2020). There is a significant amount of overlap with the best placement of solar for potential energy output, shown in oranges to reds, and the region least constrained to additional distributed generation in southern Vermont. There is also some overlap in further west southern Vermont for the best placement of wind for potential energy output.

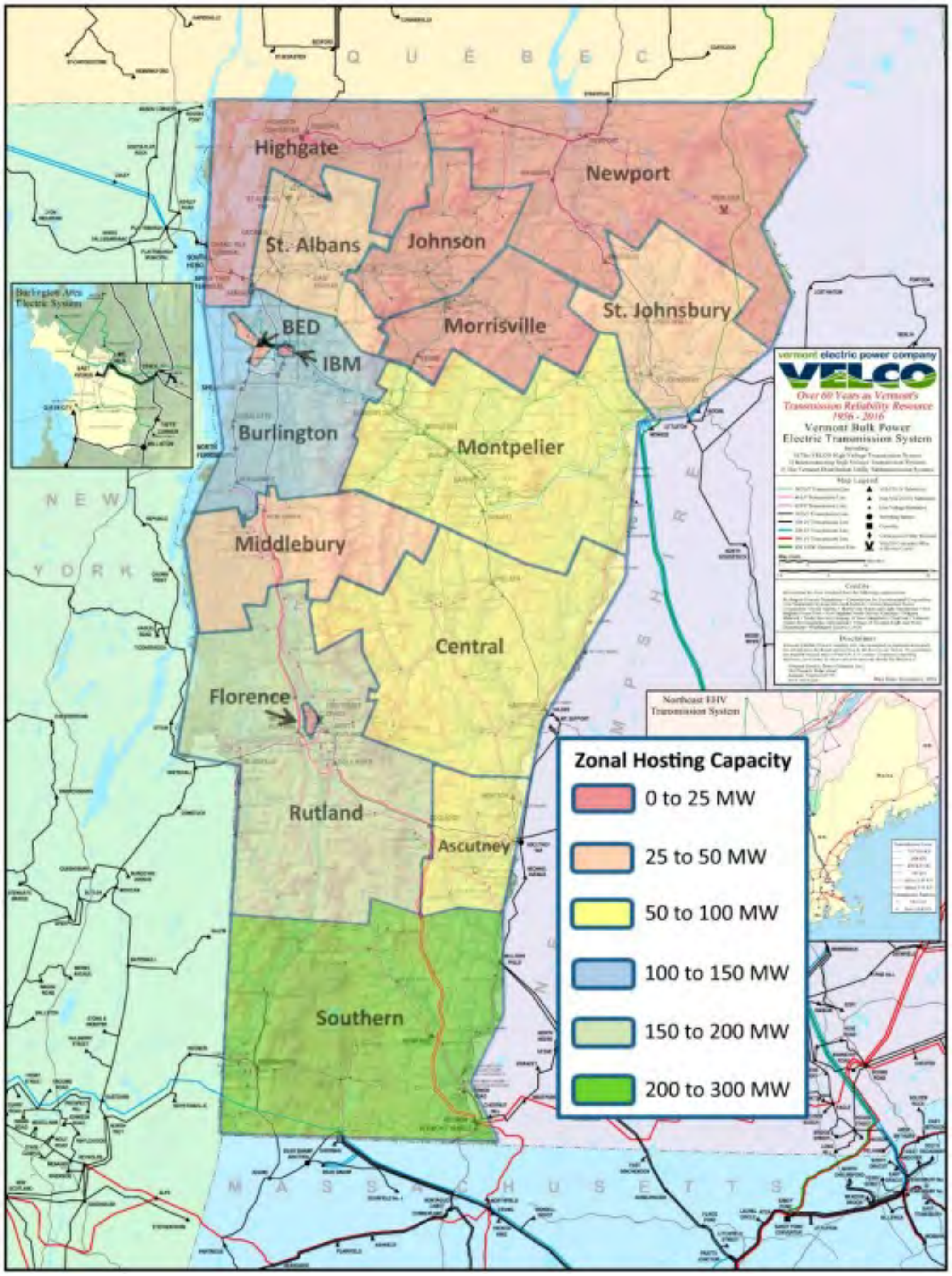


Figure 6-9: Capacity for additional distributed electricity generation across Vermont in zones (VELCO, 2021)

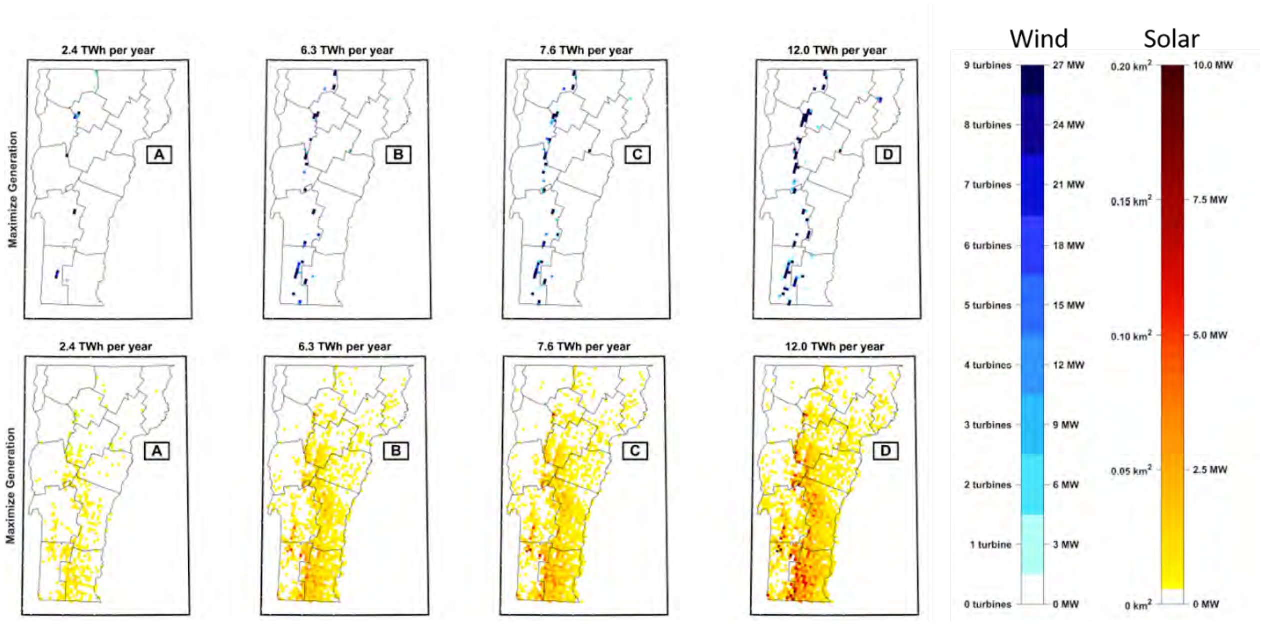


Figure 6-10: Potential placement of wind and solar power generation resources to maximize production using weather data (Thomas and Racherla, 2020)

5.4.1.4 Northern Vermont

There are many balancing acts to be achieved when planning the future of the grid. Ideally, the grid will be capable of supporting electricity needs at an affordable price with very high reliability using only renewable energy. One example of the balancing act for investing in the grid comes from the Northeast Kingdom in Vermont, where the transmission capacity to import and export electricity is limited, and renewable energy development is already high. Wind generation in northern Vermont is curtailed 13% of the time (Root, 2016), mostly due to reliability concerns from ISO-NE, which calls for the wind generators to shut down in order to maintain grid stability in the event of a line loss (an electric transmission line going down). New transmission lines are extremely expensive and would need to be approved by the PUC and ISO-NE, and the costs will, eventually, be passed to consumers.

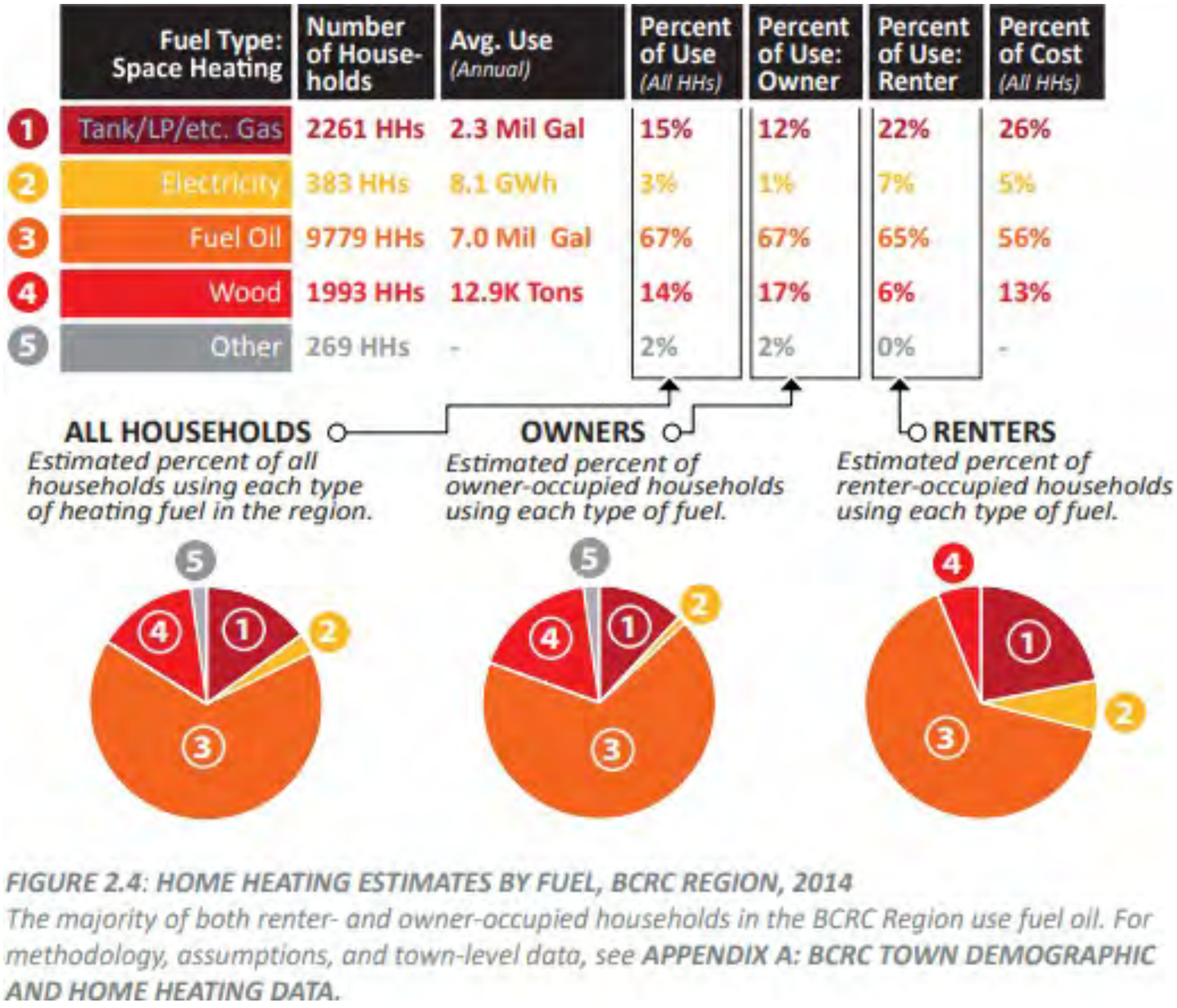
There are a couple of options for adding more renewable energy in the area and/or reducing curtailment of the resources that already exist there. One option is to invest in higher capacity T&D, and the other is to focus on transitioning as much energy use in the region as possible to electricity and using demand-side management to time the use of energy with the production from renewables. Incentivizing resources like high performance computers or data centers, which use a lot of electricity, to the region and other areas where there is a lack of additional distributed generation capacity can help to utilize locally generated energy that would otherwise be curtailed because of the constraints of the transmission network. Mobile batteries (such as the Nomad units being developed in Vermont; see https://www.nomadpower.com/) used in the Northeast Kingdom to absorb energy from renewable sources and transport it to demand centers like Burlington could help with short-term transitions as investments in the grid are being planned.

5.4.1.5 Sub-State Plans

Vermont Act 174, passed in 2016, requires every county in Vermont to formulate individual energy plans to meet the statewide comprehensive energy plan (CEP). These plans are available from the Vermont Department of Public Service (VT Department of Public Service, 2021). The plans enumerate several strategies on the path towards the state's CEP goal to be 90% renewable by 2050. Bennington County has several energy goals outlined in its report, including, to "assure diversity in the mix of energy sources to minimize the impacts of a supply restriction in any particular fuel" and to increase the local generation of energy to expand energy options to the population there. The county also expected further population decline (Bennington County Regional Commission, 2017). The northwest regional planning commission's energy plan brings to light the relationships between counties by looking at residents' reliance on employment in Chittenden County and examining the potential to benefit the county and state by supporting renewable energy generation to supply Chittenden County's growing electric load (Northwest Regional Planning Commission, 2017). Chittenden County's 2018 ECOS plan includes a helpful color map showing where wind and solar has good potential and low constraints (Chittenden County Regional Planning Commission, 2018). One example of advanced sub-state planning can be seen in the city of Burlington, which already produces all its electricity from renewables and is now considering the Net Zero Energy plan, a comprehensive energy approach to reducing the city's GHG impact (Kallay et al., 2019). A large component of Burlington's plan is district heating, which has the potential to be more efficient and may save money when compared with the costs of installing new technology in each downtown building.

5.4.2 Energy Equity

Vermonters who have the highest energy burden are, on average, using less energy than those with low energy burden (Duval et al., 2021). Despite the fact that households with the highest energy burden are contributing less to climate change, climate change is likely to have more impact on those households as increasing temperature extremes increase energy consumption (Raimi and Wason, n.d.). When developing new energy policies, inviting a diverse spectrum of people to the table is key to finding solutions that work for voices heard less often. The California PUC, for example, has a program to compensate participation in the decision-making process and recently began requiring that written public comments be specifically addressed in the decision-making process (Spelt, 2020). In Oregon, data is being gathered to better understand how these incentives help and which populations those incentives end up reaching (Rubado, Griguhn, and Novie, 2018). Similar data collection in Vermont could help facilitate the reach of incentives to the population for which making the changes mandated by the GWSA will have the highest burden. Figure 6-11 depicts the percent of heating types within Bennington County by owner and renter households; it shows that renter households are more likely to heat with higher priced heating fuels. Incentive programs have the potential to have greater impact for Vermonters with higher energy burden, such as weatherization; a focus on energy equity will help ensure that Vermont programs offer incentives that can help reduce energy burden.



	Fuel Type: Space Heating	Number of Households	Avg. Use (Annual)	Percent of Use (All HHs)	Percent of Use: Owner	Percent of Use: Renter	Percent of Cost (All HHs)
❶	Tank/LP/etc. Gas	2261 HHs	2.3 Mil Gal	15%	12%	22%	26%
❷	Electricity	383 HHs	8.1 GWh	3%	1%	7%	5%
❸	Fuel Oil	9779 HHs	7.0 Mil Gal	67%	67%	65%	56%
❹	Wood	1993 HHs	12.9K Tons	14%	17%	6%	13%
❺	Other	269 HHs	-	2%	2%	0%	-

ALL HOUSEHOLDS
Estimated percent of all households using each type of heating fuel in the region.

OWNERS
Estimated percent of owner-occupied households using each type of fuel.

RENTERS
Estimated percent of renter-occupied households using each type of fuel.

FIGURE 2.4: HOME HEATING ESTIMATES BY FUEL, BCRC REGION, 2014
The majority of both renter- and owner-occupied households in the BCRC Region use fuel oil. For methodology, assumptions, and town-level data, see ***APPENDIX A: BCRC TOWN DEMOGRAPHIC AND HOME HEATING DATA.***

Figure 6-11: Types of heat used in Bennington County, Vermont by rented and owned housing and the percent of cost (Bennington County Regional Commission, 2017).

Note: By comparing heat sources where the percent of use is lower than the percent of cost, the figure shows that renters, who have more limited control over the heating option, use a greater percent of the heat sources that come with higher costs.

5.5 IMPACTS OF CLIMATE CHANGE ON ENERGY INFRASTRUCTURE AND SOLUTIONS

Not only are the sources of energy we use driving climate change, but climate change is driving how and when we consume energy and increasing the risk of damage to infrastructure from weather events. Increasing temperature will lead to increased air conditioning load in the summer and shoulder seasons. However, as shown in Figure 6-8, the base load is not expected to rise for a few years. Additionally, cold climate heat pumps, which can be used for both heating and cooling, are expected to increase cooling load on the grid. In other words, heat pumps are not expected to replace central cooling systems in most cases; instead, Vermonters will add climate heat pumps to their existing systems (VELCO, 2021). On average, warmer winters will lead to less energy used to heat homes, but the large variability in winter temperatures may mean that Vermonters prepare for the coldest cases. Not only are "normal" weather patterns changing, but the energy in storms also is increasing, which means that more intense storms are expected in the future (VELCO, 2021). These changes are leading to a public and policy focus on resilience of infrastructure, which prioritizes preparation for and mitigation of high impact, low probability events.

Electrifying heating and transportation within the state puts more pressure on the electric grid to be reliable and resilient. The exceptionally cold weather in February, 2021 in Texas illustrate the effects that more extreme weather events can have on infrastructure, and these significant infrastructure failures can result in deaths (Englund, 2021). Hurricane Irene caused widespread damage in Vermont, and damaged millions of dollars of infrastructure (Hewitt, 2016). Large events tend to expose often neglected interdependencies among infrastructure systems. For example, damage to the transportation system can increase the time it takes to repair damaged electricity infrastructure. Conversely, electricity outages can cause traffic lights to go out, grocery store coolers to go down, water treatment plants to malfunction, etc.

Figure 6-12 (top) shows weather events in Vermont for the past eleven years by month and event type (thunderstorm wind, ice, wet snow, and gradient wind). Weather analysis for future climate scenarios in the draft of the latest long-term transmission plan from VELCO concludes that flooding and high precipitation events are occurring at higher intensities and conditions for more intense storms will continue to be prevalent, especially in the late fall. Figure 6-12 (bottom) shows the cumulative hours in which customers' electricity went unserved in the Green Mountain Power service zone by event type and month from 2008 to 2019. The clear outlier are the outages occurring in October, November, and December, which by far have the most unserved customer hours. Electricity outages are often caused by tree limbs falling or tree failures during severe weather events, and large trees falling onto electric lines cause long and costly outages (Green Mountain Power, 2019).Thus, an essential part of the resilience strategy for reliable and resilient electricity supply is maintaining rights-of-way with consistent tree trimming.

While not a requirement, ensuring backup systems for heating in Vermont households is suggested. Most heating options will not operate under prolonged electricity outages. The options that do not fail are far more limited, the most common of them are traditional wood stoves. Another option is developing microgrids that combine backup batteries and solar energy to provide a backup option for power outages. While it may not be feasible for every household to have a back-up wood stove for heating and solar plus storage for transportation, a community building with a wood stove and solar plus storage back-up for emergency purposes is a more efficient option that can increase the resilience of the community to extreme weather events (see Community Development chapter). Backup electricity storage, especially when paired with solar, also has the potential to make many systems more resilient to electricity outages. Homes, hospitals, grocery stores, and water treatment plants could use the backup electricity storage. Undergrounding electric lines can prevent some outages from occurring, especially due to wind, ice, and snow; however, underground lines are far more expensive and, if they do need to be repaired, repair times take significantly longer.

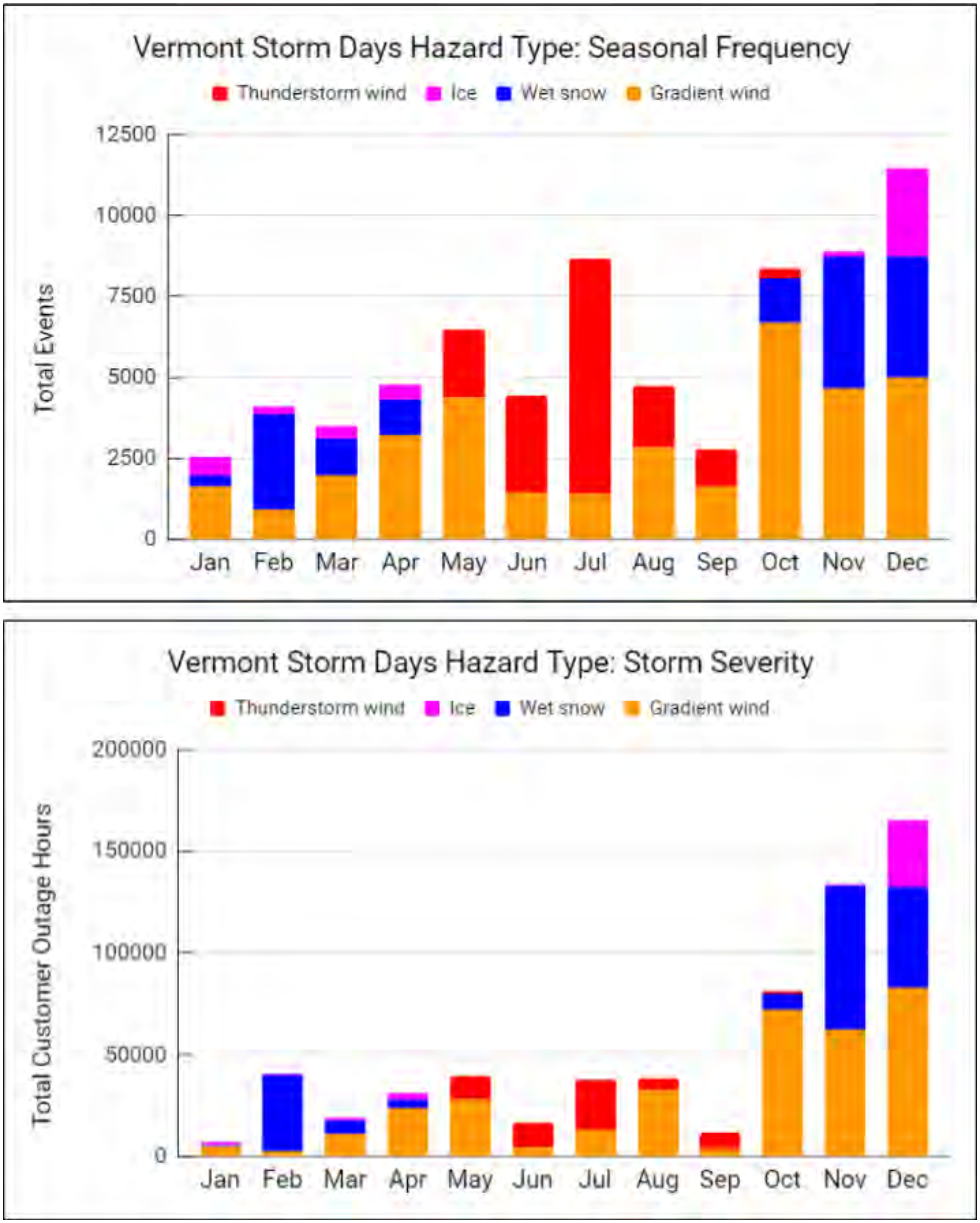


Figure 6-12: Top: Weather event types by month with data 2008–2019. Bottom: Electricity outages by unserved customer hours, month, and weather event types 2008–2019 (Schafer, 2021).

5.6 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

Confidence level	**Very high**	**High**	**Medium**	**Low**
Description	Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus	Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

<u>Key Message 1:</u> Vermont drivers have the highest average miles traveled per capita in the Northeast, and transportation is the largest source of greenhouse gas emissions in the state. The thermal energy use of the state is the largest use of energy and a close second to the largest source of emissions in Vermont. Reducing energy use in these sectors by choosing more efficient vehicles, heat sources with fewer emissions, and weatherizing homes will help Vermont meet its energy goals.	
Confidence level	Very High
References	See chapter text.

<u>Key Message 2:</u> The electricity in Vermont has the lowest carbon intensity in the country. Electrifying as much transportation and thermal energy use as possible will significantly reduce Vermont's carbon footprint.	
Finding	High
References	See chapter text.

<u>Key Message 3:</u> In the short term there is plenty of extra power line capacity to serve significantly more load in Vermont; however, some areas of Vermont have very limited capacity to support further renewable energy generation. Areas where there is limited generation hosting capacity could be prioritized for shifting local energy use to electricity to reduce congestion on local transmission lines. The priority in areas with extra generation hosting capacity can be two-fold: building new renewable generation and electrifying local energy use.	
Finding	Medium
References	See chapter text.

Key Message 4: The storms that cause the most frequent power outages will become more, increasing the frequency of power outages, particularly in winter. Vermont can increase resilience with distributed solar and storage, secondary heating systems (e.g., wood), and community buildings with resilient heating solutions.	
Finding	Medium
References	See chapter text.

5.7 ACKNOWLEDGEMENTS

I would like to acknowledge Jay Schafer of Northview Weather for the contribution of his analysis on electricity outages during storm days in Vermont. I would also like to thank Ed McNamara, Jared Duval, and Paul Hines for taking the time to review this chapter, and Gillian Galford and Laura Edling for the opportunity to collaborate on the Vermont Climate Assessment.

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6 RECREATION AND TOURISM

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6.1 KEY MESSAGES

Winter

- Downhill skiing, with the help of snowmaking, will likely remain largely viable in Vermont up until approximately 2050. By 2080, the Vermont ski season will be shortened by two weeks (under a low emissions scenario) or by a whole month (under a high emissions scenario), and some ski areas will remain viable.
- Winter temperatures are increasing in Vermont, reducing the length of season for most snow sports.
- February Median Flow, a measurement used by ski areas to collect water for snowmaking, has steadily increased across Vermont.

Summer

- Summer recreation activities in Vermont will continue to be popular, with water-based activities likely to increase in interest as air temperatures rise. However, water quality issues will also become more prevalent.
- Vermont may see an increase in summer "seasonal climate refugees" as the rise in temperatures nationwide draws visitors looking to escape extreme heat.
- Vermont has the potential to increase tourism revenue via gastrotourism and agritourism as the growing seasons lengthen.

Fall/Spring

- Transition seasons are becoming more important for tourism and recreation as Vermont is already experiencing warmer temperatures in fall and spring.
- Trees, particularly sugar maples, are an important aspect of many fall/spring recreation activities (leaf peeping, maple syrup, apple picking), but may be negatively affected by warmer temperatures.
- Fall and spring seasons offer new opportunities for lower-cost recreation and tourism opportunities that attract a wider range of potential visitors.

6.2 INTRODUCTION

As stated in the 2014 Vermont Climate Assessment (VCA), “Recreation and Tourism go together in Vermont.” Vermont’s rich and mountainous settings and its cooling lakes and streams offer opportunities for a wide variety of recreational activities across the seasons, drawing visitors from all over the country and internationally. With the exception of the year 2020, which was ravaged by the COVID-19 pandemic, the Vermont tourism industry generates nearly $3.0 billion a year (Vermont Agency of Commerce and Community Development, 2021), making recreation and tourism one of the most lucrative industries in the state. Outdoor recreation, as a top driver of Vermont’s economy, offers the potential for a wide variety of satisfying careers, thus encouraging college graduates and other young people to remain in Vermont and drawing others to the state.

Currently, Vermont tourists mainly come from the Northeastern states (Vermont Department of Tourism and Marketing, 2018), but with climate change leading to elevated temperatures, Vermont may see an increase in visitors from other areas looking to escape the extreme summer heat. Likewise, as global temperatures increase, Vermont’s transitional seasons of spring and fall are expected to lengthen as rising temperatures result in shortened winter overall (see Climate Change in Vermont chapter). Given the seasonality of most of Vermont’s outdoor recreation opportunities, climate change is likely to affect each recreation-based sector in a unique and challenging way. The Vermont ski industry will need to adjust to new snowmaking requirements, syrup makers will be forced to tap maples earlier, and hiking trails will degrade more quickly due to extended hiking seasons and/or increased erosion. It is undeniable, however, that climate change will have lasting effects on the way Vermonters and tourists recreate.

Recreation activities and tourism opportunities in Vermont range from high-priced to free, with seasonal variation. Participation also varies across socioeconomic and demographic categories. Some sports and outdoor activities (skiing, boating, snowmobiling) tend to be more exclusive: they draw a wealthier group of participants because of the costs associated with participation. Other activities (more likely to be those in the spring, summer, and fall seasons) are lower in cost or even free: sightseeing, hiking, walking for pleasure, birdwatching, fishing, and other group and individual activities. Decades of recreation research have shown that racial demographic groups are differentially represented in outdoor recreation, sports, and tourism activities, and this is also true in Vermont, where the state population is reported to be about 94 percent white (US Census Bureau, 2019). The effects of climate change may have implications for this lack of diversity, however, as more out-of-state visitors from more diverse parts of the country (Mid-Atlantic and Central regions, for instance) may be drawn to Vermont, especially during longer summer and shoulder seasons. More climate change refugees may also see Vermont as a haven for new residences. In short, climate change offers Vermont new opportunities to diversify and offers new challenges to become a more inclusive state.

For the purpose of the 2020 Vermont Climate Assessment, the effects of climate change on Vermont's recreation sectors will be identified based on the predominant recreation seasons: winter and summer are each discussed individually below, with fall and spring combined given the similarities in recreation opportunities for the two transitional seasons.

Box 7.1: COVID-19 and Recreation in Vermont

According to the Vermont Department of Forests, Parks and Recreation, the most important outdoor recreation issue in 2020 was an increase in outdoor participation. Given restrictions enacted during the COVID-19 pandemic, more Vermonters sought outdoor experiences and new outdoor activities. There was a noticeable increase in trail user days for hiking and mountain biking; Nordic and backcountry skiing surged; the number of hunting and fishing licenses issued increased; campgrounds were at capacity; and a myriad of other activities done for the sole purpose of spending time outside all had a rise in participation. These types of recreation opportunities have in turn lead to greater economic opportunities for outdoor-related businesses that provide gear and equipment, information about trail networks or camping sites, and skill-building education. Increasing numbers of recreationists has also driven patronage to businesses in the more rural communities and outer regions of the state, increasing revenue for these types of business statewide (VOREC, 2020).

Despite this surge in recreation users, money spent on traditional aspects of Vermont's recreation and tourism industry—such as lodging, meals, and alcohol—plummeted by over $300 million (see Figure 7-1). It is impossible to know what the coming years will hold, but outdoor recreation provides a healthy outlet for people to cope with the dramatically changed times (Landry et al., 2021).

So while Vermont saw a decline in recreation and tourism revenue due to the COVID-19 pandemic, there was in fact a steady increase in people getting outside and recreating (VOREC, 2020).

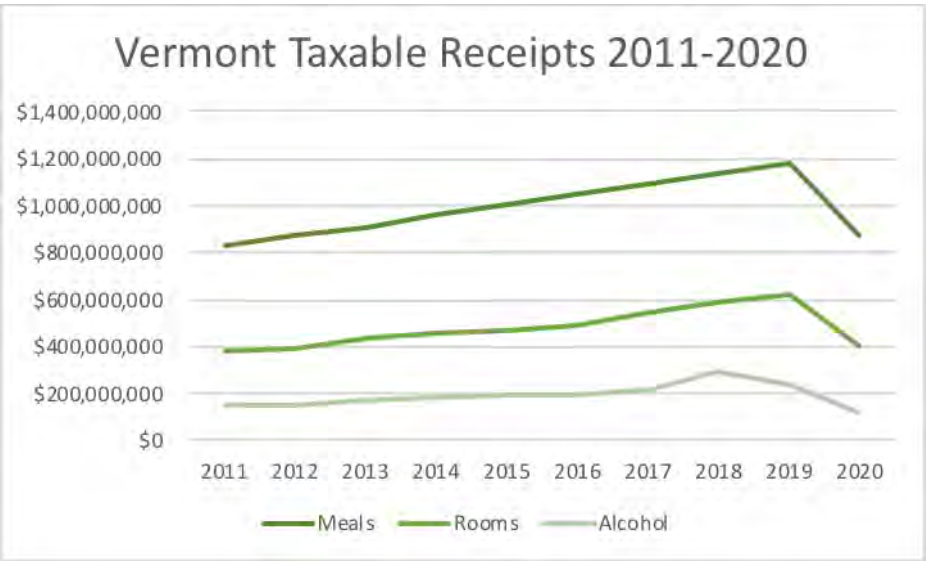


Figure 7-1: Taxable receipts 2011–2020, data collected from the Vermont Agency of Administration

6.3 WINTER

Winter recreation is an integral part of Vermont's identity as well as a significant money-maker for the state economy (Vermont Department of Tourism and Marketing, 2018). Yet Vermont's traditional winter season will certainly be shortened due to climate change. Despite this, skiing – which attracts millions of tourists to the state each year – will most likely be viable through nearly the end of the century. Winter sports that generate less revenue than skiing and that have fewer options for climate change mitigation, such as snowmobiling and pond hockey, will be particularly vulnerable to warming temperatures and variable precipitation in the coming decades. Nordic skiing may be able to maintain the length of its season by implementing creative snow preservation tactics, but an adequate amount of snow will have to fall and be collected.

Winter precipitation in Vermont has increased over the past century. Snowfall, an integral aspect of many winter recreational activities, peaked in the 1960s and 1970s and has declined since, especially in southern Vermont (see Climate Change in Vermont chapter). In one New Hampshire study, the "backyard hypothesis," which states that urban skiers are more likely to head to the mountains on days that they see snow in their own backyards, was proven to be true (Hamilton et al., 2007). If Vermont continues to receive adequate amounts of snow, or if resorts can make enough snow to operate ski mountains, increasingly strong marketing campaigns will be needed to draw visitors from states with less regular or productive snowfalls.

Along with precipitation, temperature is also predicted to increase over the next century in Vermont (see Climate Change in Vermont chapter). If temperatures generally remain under 32 degrees Fahrenheit, this could mean an increase in annual snowfall. Average winter temperatures in Vermont are generally well below 32 degrees Fahrenheit (see Figures 7-2, 7-3, 7-4) but have steadily increased by roughly 3.3 degrees Fahrenheit since the early 1900s.Winter temperature variability also is significant, as temperatures may range more widely during the winter season (see Climate Change in Vermont chapter).

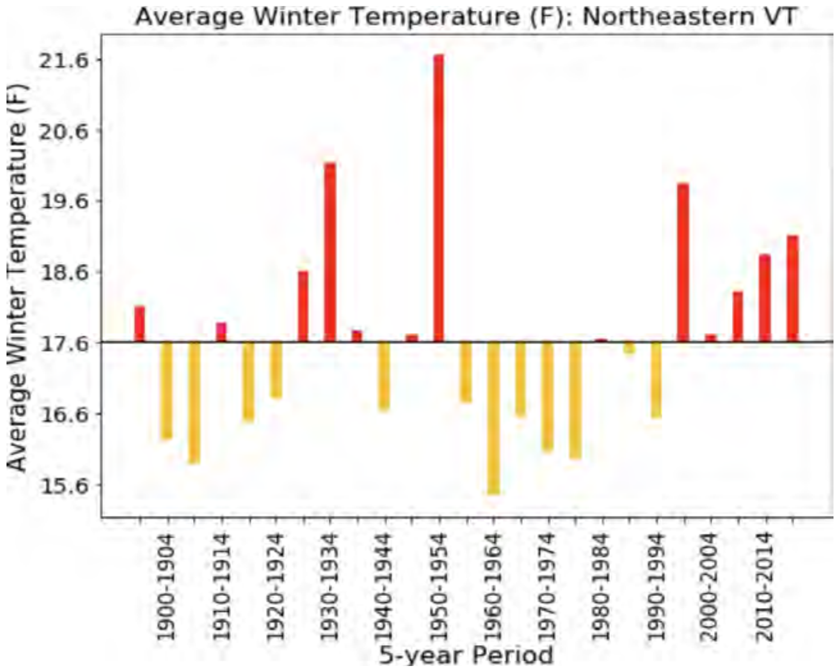


Figure 7-2: Average Winter Temperature: Northeastern VT

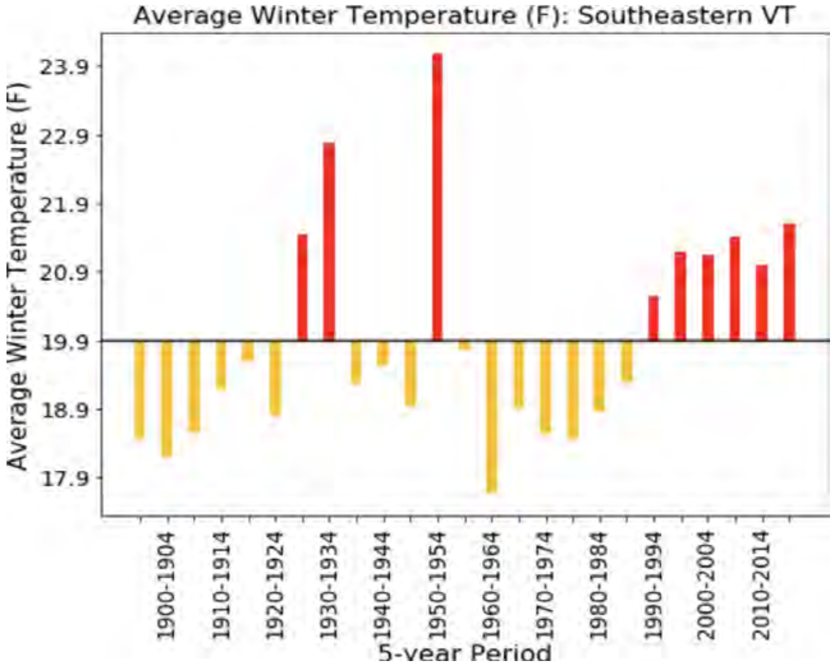


Figure 7-3: Average Winter Temperature: Southeastern VT

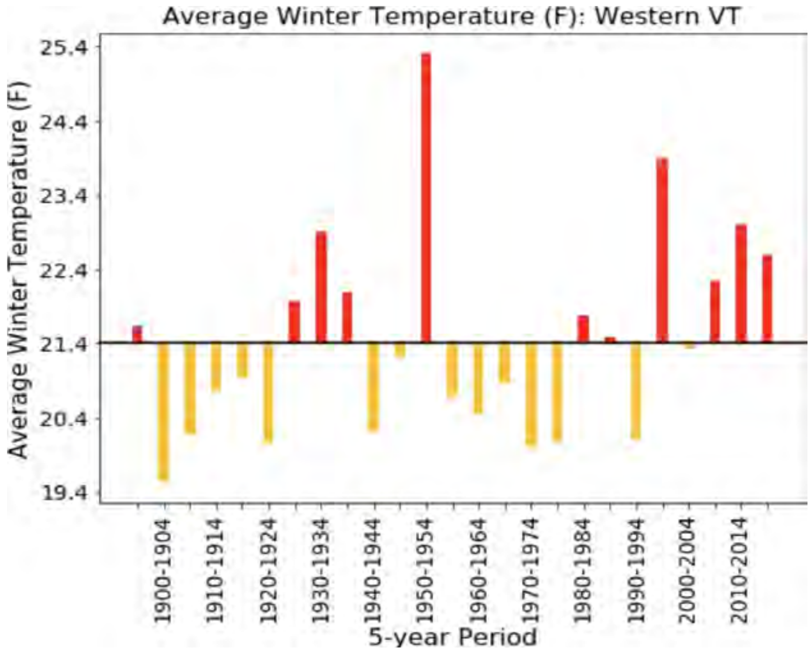


Figure 7-4: Average Winter Temperature: Western, VT

Temperatures must remain at or under 28 degrees Fahrenheit for ski areas to make snow (Bark et al., 2010). If the window of time when air temperature is at or below 28 degrees continues to shrink, snowmaking capabilities will be limited. For example, one 2018 study in the White Mountains of New Hampshire found a decrease in snowmaking opportunities in the early ski season and a projected further decrease in optimal snowmaking weather in decades to come (Wilson et al., 2018). The annual average air temperature in the White Mountain region of New Hampshire has increased by 1.8 degrees Fahrenheit since 1960 (Campbell et al., 2010). Vermont has been warming at a similar pace, with an average winter temperature increase of 3.3 degrees Fahrenheit (see Climate Change in Vermont chapter). This increase in temperature will likely be an especially serious issue where warming trends are most acutely present, as in southeastern Vermont (see Climate Change in Vermont chapter).

Through 2050, almost all ski areas in Vermont should be able to operate and contribute tourism dollars to the Vermont economy (Steiger et al. 2019, Scott et al., 2020)—and many will likely continue to operate as late as 2080 (Scott et al., 2020). Despite this, smaller ski areas at lower elevations, such as Suicide Six in Pomfret and Cochrans ski area in Richmond, will be faced with the most pressing climate-change challenges in the coming decades, as warming trends are predicted to continue (VCA, 2014).

Vermont snowmakers wishing to make snow must adhere to the water withdrawal laws outlined by Chapter 16 of the Vermont Agency of Natural Resources Environmental Protection Rules. This law essentially states that ski areas may only withdraw water from a stream until it reaches its February Median Flow levels (Shanley & Wemple, 2001). February Median Flow is an average of the median stream flow rate for every single day of February. Because stream flow is at its lowest point in February, the State of Vermont feels that withdrawing water beyond the point of February Median Flow would disrupt stream ecosystems and should therefore not be allowed. Figure 7-5 shows an increase in February Median Flow since the year 1960 – an increase that is consistent with overall streamflow increases over the past century in Vermont (see Water Resources chapter). This observed streamflow increase can most likely be attributed to loss of snowpack and early snowmelt during February as well as increased winter precipitation (see Water Resources and Climate Change in Vermont chapters).

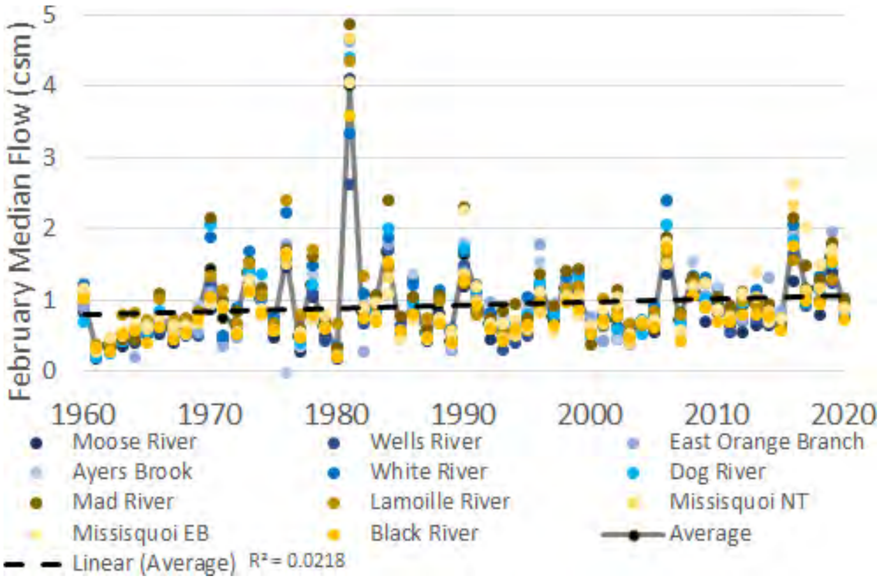


Figure 7-5: February Median Flow (csm) for gauge stations in the St. Lawrence River Basin (western VT; yellow hues) and Connecticut River Basin (eastern VT; blue hues)

Source: Water Resources chapter, data from USGS and Water Resources chapter, data collected from the USGS streamflow database.

Although the Vermont ski season is certainly vulnerable to climate change, the state has been included in some promising projections. In one snow reliability study, all researched northeastern US states other than Vermont were projected to lose at least half of their ski areas by the mid-2050s under a high emissions scenario (Steiger et al., 2019). Skiing in Vermont is projected to be economically feasible at most resorts until about 2080 (Scott et al., 2020). Vermont could potentially capitalize on this resiliency and may see increasing demand for skiing and related winter activities through mid-century. To effectively capture this market, Vermont ski areas would have to meet the 100-day and Christmas holiday indicators. The 100-day indicator states that a ski resort must have snow coverage of at least 30 centimeters, for seven out of ten winters, during the 100 day period between December 1 and April 15th (Bürki, 2000 and Steiger & Abegg, 2013). The Christmas holiday indicator (covering the Christmas and New Year's holiday period) focuses on the likelihood of a ski area having a snow depth of at least 30 centimeters between December 22 and January 2 (Scott et al., 2008). Snow coverage of 30 centimeters to 50 centimeters (12 to 20 inches) is needed for skiers and riders to recreate on the mountain safely (Bürki, 2000 and Steiger & Abegg, 2013). The 100-day and Christmas holiday indicators represent periods of time that are integral to the financial success of a ski area (Steiger & Abegg, 2013). Currently, the average length of the ski season in Vermont is 127 days (Scott et al., 2020). By the middle of the current century, though, this number is expected to drop to 115 days under a low emissions scenario, and to 111 days in a high emissions scenario (Scott et al., 2020). By the 2080s, the Vermont ski season is expected to last 113 days under a low emissions scenario or 96 days if a high emissions scenario prevails (Scott et al., 2020). Steiger and Abegg (2013) suggest that if the Vermont ski season dips below the 100-day indicator or cannot open during the Christmas holiday window, ski resorts may not make enough money to stay open. Despite potentially losing an entire month of the ski season by 2080, studies project that Vermont will retain the highest number of season days in the Northeast (Scott et al., 2020) – advantaging tourists who can be flexible with their leisure travel. The Vermont ski industry may find that skiing in Vermont will be possible for the majority of the twenty-first century.

In addition to its effects on downhill skiing, climate change will necessitate adaptations from other winter sports in Vermont. According to a study conducted at the University of Vermont, snowmobilers in Vermont have already reduced their hours of participation in the activity in response to climate change (Perry et al., 2018). This study found that 44.7% of snowmobilers surveyed have observed a shortening of the winter snowmobiling season, and in response, 30.7% of these respondents now snowmobile less often (Perry et al, 2018). Snowmobiling in Vermont has a length of season threshold, or number of days with adequate snow cover. This length of season threshold in Vermont is approximately 79 days; any season with over 79 days will most likely report an increase in snowmobiling, whereas any season under 79 days will tend to report a decrease in snowmobiling (Perry et al., 2018). Unless Vermont continues to have adequate snow cover for 79 days or more, snowmobiling in the state will lose participants. Unlike ski mountains, snowmobile trails do not have snowmaking to help produce snow coverage. The reliance on adequate snow cover across a vast terrain, along with the current climate change trends, means that snowmobiling may be unsustainable in Vermont in the coming decades (Perry et al., 2018). This research also aligns with a nationwide study of outdoor recreation activities that predicts that snowmobiling is one of the winter activities most vulnerable to climate change (Bower and Askew, 2018).

In addition to the statewide increases in precipitation and temperature, some Vermont lakes have been thawing slightly earlier as a result of climate change (see Climate Change in Vermont chapter). Ice-out refers to when lakes and ponds begin to lose their winter ice cover (Hodgkins et al., 2002). Earlier annual ice-out dates have negative implications for ice-related recreation activities, including ice fishing, and outdoor ice hockey and ice skating. If the ice is not thick enough throughout a winter, or only viable for a short period of time, participation in outdoor ice-related recreational activities will decline. Further, winter drowning deaths might increase. In a recent study of 10 countries in the Northern Hemisphere, researchers found that winter drowning incidents typically occurred when the air temperature hovered between 0 degrees Celsius (32 degrees Fahrenheit) and -5 degree Celsius (23 degrees Fahrenheit) (Sharma et al., 2020). This range of temperatures coincides with Vermont's average winter temperature range (see Climate Change in Vermont chapter). Rates of drowning were highest late in the winter season, when the ice becomes unstable (Sharma et al., 2020). As Vermont's temperatures continue to increase, locations that offer recreational ice use should pay close attention to ice conditions when air temperature rises above 23 degrees Fahrenheit, and frequently update the public about changes in ice thickness.

The Pond Hockey Classic, a tournament first established at New Hampshire's Lake Winnipesaukee, must be increasingly attentive to ice conditions in the future. The Pond Hockey Classic occurs at several locations across the Northeastern United States, including Lake Champlain. The Classic has had to cancel its events several times in the 2010s due to warm weather (Fairley et al., 2015). This event, which brings hundreds of participants to Colchester each year, typically prepares backup plans if the original host location is deemed unsafe – yet in some years, such as 2011, even the ice at backup locations failed to provide a space for recreation (Fairley et al., 2015). As Vermont winters continue to warm, the Pond Hockey Classic and similar events may need to move to indoor skating rinks.

Box 7.2: Nordic Skiing and Snow Storage: Creative Climate Change Solutions

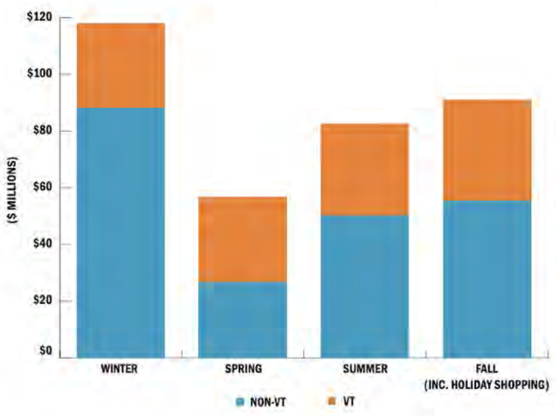
Between the years of 2018 and 2020, UVM master's student Hannah Weiss conducted a study in Craftsbury, VT, to assess how storing snow piles over the summer may help extend the Nordic ski season there. In her experiment, two 200 m^3 piles of snow were collected and protected under layers of wood chips (Weiss, 2021). Volume changes in the snow pile were observed through laser scanning. The snow piles maintained most of their mass when covered with wood chips and a reflective sheet. Hannah and her team used this information to then create an even larger snow pile of 9300 m^3 in the summer of 2019, once again protecting the snow with wood chips and a reflective sheet. The snow pile ended up retaining 60% of its original snowmass, which was enough snow for the Craftsbury Outdoors Center to open their facilities on time for that season (Weiss, 2021). The results of this study declared this method of snow storage technically, financially and environmentally feasible for this location in Vermont, and could potentially help extend the length of the Nordic season in other northern locations.

6.4 SUMMER

As found in the 2014 VCA, increased temperatures due to climate change are likely to extend the length of the summer recreation and tourism season. Vermont summer temperatures have already risen an average of 1.84 degrees Fahrenheit since 1960 (see Climate Change in Vermont chapter). In comparison to the negative effect that increased temperatures will have on winter recreation in the state, it is believed that the extended summer season will benefit Vermont's summer tourism and recreation industries and economy. In Vermont, direct spending by users of outdoor retailers and service providers totals $2.8 billion annually. (Nationally, the outdoor recreation industry comes in at $646 billion, and is being measured as part of the nation's gross national product.) Historically, summer sees the most recreation user days in the state, and although summer activities like hiking, biking, and boating tend to be less cost-prohibitive (compared to downhill skiing and fees associated), the activities themselves don't usually have a huge impact on the state's economy, but meals and lodging for out-of-state visitors add a sizable revenue to the state's economy.

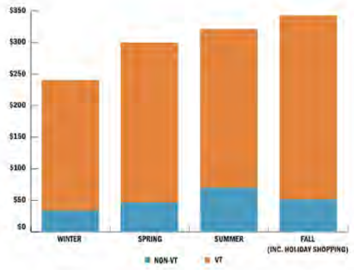
This will likely increase with climate change. The Vermont Department of Forests, Parks and Recreation predicts that as temperatures increase nationally, Vermont will see an increase of Southern-state visitors during the summer. These are visitors looking to escape the hotter months in their region—a form of seasonal climate refuge. These travelers will likely drive an increase in summer tourism and thereby revenue in recreation sectors during typically lower-revenue months of the year (Snyder, personal communication, May 21, 2021).

SPENDING PATTERNS IN SKI TOWNS



OVERALL SPENDING

An analysis of credit card data from 35 ski towns reveals that tourism dollars drive spending around winter recreation centers.



SPENDING PATTERNS IN THE BURLINGTON AREA

For comparison here is the similar data for the Burlington area.

SOURCE: VISAVUE CREDIT CARD DATA

PERCENTAGE OF OUT OF STATE SPENDING IN SKI TOWNS

RESTAURANT SPENDING
WINTER **79%**
SPRING **57%**
SUMMER **69%**
FALL **71%**

MOTOR FUEL SPENDING
WINTER **49%**
SPRING **32%**
SUMMER **41%**
FALL **38%**

LODGING SPENDING
WINTER **94%**
SPRING **86%**
SUMMER **92%**
FALL **92%**

RETAIL SPENDING
WINTER **61%**
SPRING **47%**
SUMMER **57%**
FALL **53%**

VERMONT TOURISM 2017 BENCHMARK REPORT
2018 RELEASE

In addition to the effects of warming temperatures, the COVID-19 pandemic also created an overall uptick in Vermont residents seeking summer recreation. According to the 2020 Vermont Outdoor Recreation Economic Collaborative Report, many recreation locations (trailheads, beaches, campgrounds, etc.) were above capacity for much of the 2020 summer. With an increase in new users accessing these areas, there appeared to be a general lack of knowledge about best practices and ethics that caused higher than average levels of degradation within trail systems, waterways, and on recreating infrastructure. Because of this, the $2 trillion Coronavirus Aid, Relief, and Economic Security (CARES) Act included funding to improve public access to the outdoors. Vermont received $1.6 million which will include upgrades to many fishing and boating access areas; road and trail maintenance at Wildlife Management Areas; as well as a mobile app that will assist the public by educating about outdoor recreation best practices, thereby continuing to make safe places to recreate in Vermont (VOREC, 2020).

The Vermont Department of Forests, Parks and Recreation noted that in order to be more resilient to overuse, Vermont could benefit from a more robust portfolio of accessible state lands, which would in turn provide more diversified opportunities for recreation (Snyder, personal communication, May 21, 2021). An added benefit of this would be a need for recreation staff, creating more jobs for Vermonters. Additionally, creating more recreation-friendly state land would also create opportunities to work in partnership with various government and local non-profit organizations, further bolstering the economy and workforce.

Box 7.3: Impacts of Climate Change on Vermont Mountain Biking

Abby Long, the Executive Director of Kingdom Trails in East Burke, VT, noted that while an extended summer biking season will mean more users and revenue, it also means having to re-allocate budget line items and extend the need for staff. Yet at this phase of climate change it's still rather unpredictable, which makes it hard for her to make these decisions. She also mentions that extreme drought and catastrophic rain events both have indelible effects on a trail's health for the foreseeable seasons, and new users may not know trail etiquette designed to maintain healthy and usable trails (Long, personal communication, March 12, 2021). The Vermont Department of Forestry, Parks and Recreation echoed this concern: "With wetter summers overall, our trails are seeing more impact from use over longer periods of time each year and with infrastructure that wasn't built with that amount of use and water or erosion in mind (Snyder, personal communication, May 21, 2021)."

With longer and hotter summers predicted, farms and growers will have an extended growing season (see Agriculture and Food Systems chapter) and agritourism and beer tourism are likely to see an increase in recreation users because of this. A recent survey conducted by UVM in 2019 and 2020 amongst licensed agritourism farms indicated that over half (59%) of the farms surveyed plan on expanding their agritourism services, and almost half (43%) intend to invest more in buildings or equipment to provide a richer agritourism experience (Chase et al., 2021). Similarly, as of 2019, the state of Vermont had a total of 68 craft breweries, ranking it first in the nation for per capita breweries (Vermontbrewers.com). It is no secret that Vermont's breweries bring tourists from near and far, often to visit in conjunction with hiking, biking, camping, or other recreation-based trips. Additionally, many of Vermont's breweries focus on sourcing ingredients locally, making a longer growing season beneficial for sourcing local hops and other farmed elements of beer production.

Box 7.4: Clean Water=Clean Beer!

After the Trump administration's rollback on EPA protections of the Clean Waters Act, craft brewers across the nation, including many in Vermont, signed a petition imploring the new Biden administration to reverse that action to ensure the nation has access to clean drinking water—and clean ingredients for beer!

Lake Champlain's 490 square miles of surface and 587 miles of shore, along with Vermont's numerous ponds, rivers, and streams, make Vermont an ideal water-based recreation oasis. The Vermont Department of Forestry, Parks and Recreation predicts that with the higher summer temperatures due to climate change, more people will pursue water-based recreation at higher rates than in the past (Snyder, personal communication, May 21, 2021). However, the issue of water quality and quantity continues to be a driving concern with stakeholders across the board. With increased air temperature comes increased water temperature, leading to water quality issues—specifically in the form of invasive species and algae blooms (see Water Resources and Fish and Wildlife in Vermont chapters)—often forcing popular beaches to close and creating areas for boaters and water enthusiasts to avoid. The recent COVID-19 pandemic also drove a boost in boat sales in the state, ranging from small watercraft like kayaks, canoes, and stand-up paddleboards to larger, motorized craft. Robert Hensley, the general manager at the new Burlington Harbor Marina, notes that new boaters are on the rise in the Burlington area and with that comes increased boater traffic and often less-informed boaters (Hensley, personal communication, July 3, 2021).

Although hunting and fishing licenses in the state have seen a steady decline since 1980, the desire to be outside and connect with the land during the COVID-19 pandemic saw a drastic bump in the amount of hunting and fishing licenses purchased, reaching levels not seen in decades (VT Fish and Wildlife Performance Based Budget Report, 2020). Prior to the pandemic, in 2019 nearly 72,000 resident anglers were estimated to have fished for almost 1.8 million days, and nearly 37,000 nonresident anglers fished for approximately 369,000 days.

Unfortunately, data from the same year shows that stream temperatures continued to increase in July, August and September, threatening the health of rivers and affecting their biodiversity and their fisheries. In an interview, President of the Central Vermont Chapter of Trout Unlimited Chase Whiting mentioned that to help mitigate the effects of climate change on Vermont rivers and streams, the state needs to first work with the Clean Waterways Act to address the amount of pollutants that enter the Vermont waterways through runoff. Secondly, Vermont needs to ensure that there is good riparian health along the banks. He also stressed the need for a plan to remove aging dams, which will reconnect rivers with their flood plains. Aging dams also have the potential to collapse in the event of catastrophic rainfall, causing severe flash-flood potential (Whiting, personal communication, March 14, 2021).

Box 7.5: 2019 Angler Revenue in Vermont

Anglers make a significant contribution to recreation and tourism in Vermont; the bulk of their spending is on food, lodging, and related trip expenses. The economic impact of sport fishing in Vermont was estimated to be $147.1 million in retail sales—providing 2,420 jobs and $16.0 million in state and local tax revenues (2020 Department of Fish and Wildlife Budget Report). However, the increase in air and water temperatures could affect the native fisheries in Vermont, thereby decreasing spending in the decades to come (see Water Resources chapter).

6.5 SHOULDER SEASONS: FALL AND SPRING

Fall and spring activities are aggregated here because these are transition seasons in Vermont—not only in terms of temperature variation, but also relative to participation in recreation and tourism activities. What patterns of climate change suggest is that annually, as the winter season becomes shorter, the bordering fall and spring recreation opportunities will increase. Currently, outdoor activities done in fall and spring bring less revenue to Vermont than do summer and winter activities. Whether this will continue to hold true as climate change changes is an issue for further research.

Fall and spring are times when Vermonters and visitors enjoy outdoor recreation such as hiking, camping, fishing, mountain biking, hunting, wildlife viewing and photography. An increase in average temperatures in Vermont has the potential to extend the length of time that people can enjoy these opportunities. Activities such as hunting can bring in revenue through permits and other travel expenses, though participation in hunting has declined in Vermont and elsewhere across the US as the population ages (see Fish and Wildlife in Vermont chapter). The slow nature of the decline in Vermont differs from other places, but hunting opportunities must be coordinated with wildlife management planning for game birds, deer, and moose populations. Fostering hunting as a fall/spring recreation opportunity in Vermont may benefit the state both economically and ecologically.

One of Vermont's most notable recreation and tourism assets is its trees. Vermont forests and orchards provide opportunities for leaf peeping, apple picking, and a thriving maple syrup industry. The maple syrup industry in particular relies heavily on the health and abundance of sugar maples (*Acer saccharum*). These trees are an environmentally-sensitive species, and climate changes—especially in the Northeast—have already caused the trees to experience negative growth trends (Oswald et al., 2018). Across the US in 2018, revenues from the maple syrup industry brought in over $182 million, with Vermont as the leader in maple syrup production—producing 1.94 million gallons in 2017 (Vermont Agency of Agriculture, 2019).

Comparing Figure 7-7 to Figure 7-8 shows the changing average open and closing season dates for maple syrup production in the US. In 2013, Vermont's opening date was March 3 and closing date was April 13. In 2021, Vermont's opening date was March 12 and closing date was April 5. Though variable over the years, this shows an average loss of 16 days in the maple syrup production season.

Maple Syrup: Average Open and Close Season Dates - States and United States, 2011-2013

State	Season Opened [1]			Season Closed [2]		
	2011	2012	2013	2011	2012	2013
		(date)			(date)	
CT	Feb 24	Feb 9	Feb 12	Mar 28	Mar 12	Mar 25
ME	Mar 10	Feb 28	Mar 4	Apr 13	Mar 28	Apr 12
MA	Mar 4	Feb 19	Feb 26	Apr 4	Mar 14	Apr 3
MI	Mar 8	Feb 26	Mar 9	Apr 6	Mar 15	Apr 10
NH	Mar 7	Feb 24	Feb 28	Apr 8	Mar 20	Apr 7
NY	Mar 5	Feb 21	Feb 27	Apr 7	Mar 16	Apr 9
OH	Feb 24	Feb 15	Feb 20	Mar 27	Mar 12	Mar 29
PA	Feb 26	Feb 16	Feb 26	Mar 31	Mar 13	Apr 5
VT	Mar 9	Feb 25	Mar 3	Apr 14	Mar 22	Apr 13
WI	Mar 15	Mar 8	Mar 25	Apr 12	Mar 18	Apr 23
US	(X)	(X)	(X)	(X)	(X)	(X)

Maple Syrup Average Open and Close Season Dates – States and United States: 2019-2021

State	Season Opened [1]			Season Closed [2]		
	2019	2020	2021	2019	2020	2021
	(date)	(date)	(date)	(date)	(date)	(date)
Maine	Mar 14	Feb 29	Mar 6	Apr 14	Apr 8	Apr 6
Michigan	Mar 13	Mar 1	Mar 2	Apr 7	Mar 30	Mar 28
New Hampshire	Mar 10	Feb 24	Mar 6	Apr 10	Mar 30	Apr 1
New York	Mar 6	Feb 19	Mar 4	Apr 7	Mar 28	Apr 2
Pennsylvania	Feb 25	Feb 18	Feb 27	Apr 1	Mar 20	Mar 24
Vermont	Mar 12	Feb 28	Mar 8	Apr 15	Apr 6	Apr 5
Wisconsin	Mar 21	Mar 7	Mar 6	Apr 14	Apr 4	Mar 31
United States	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

(NA) Not available.

[1] Approximate average opened date based on reported data.

[2] Approximate average closed date based on reported data.

Figure 7-7: Maple syrup average open and close season dates 2011–2013 (upper) and 2019–2021 (lower) (USDA NASS, 2013 and USDA NASS, 2021)

Vermont was down 21% in maple syrup production in 2021 (USDA NASS, 2021). The health of trees is crucial for syrup production and quality and is important to support an upward trend of maple syrup in Vermont. A shortened maple syrup season can mean a loss in production time and the amount that Vermont is able to produce.

Vermont trees also provide a huge tourism draw based on their autumn beauty. With warmer temperatures, the shift from bright green leaves to the vibrant colors of autumn will be delayed. Currently, most Vermont tourists come from the North/Northeast, with 21% coming from Massachusetts, 17% coming from NY, 9% coming from Connecticut, and 7% each from New Hampshire and New Jersey (Vermont Agency of Commerce and Community Development, 2020). Climate change might reduce the number of visitors if the leaf peeping time shortens or if the colors are more muted and less desirable. Drought years may lead to earlier changes in color and tend towards more browns over the flashier yellows and reds.

Apple picking in the fall is an opportunity for friends and family to spend quality time together in Vermont's orchards. Apple tree species require cool winters for productive growth and fruit production. The warming temperatures consistent with climate change may cause some of these species to expand into more northern territories (State of Vermont, 2021). The reduction in colder months, though, may affect soil health and thus threaten the productivity of apple tree species. Apples may face new challenges from diseases related to spring precipitation while the trees are in bloom, potentially creating lower grade fruits due to scabbing or damaging whole trees (see Agriculture and Food Systems chapter).

Other factors, though, may accompany longer shoulder seasons (and summer). Ticks and seasonal pests will be a factor as climate becomes increasingly habitable for them (see Human Health chapter). When temperatures are below freezing, tick populations decline; however, with warmer overall temperatures and an increased number of days with average temperatures above freezing, tick populations will increase (Vermont Department of Health, 2018). Warmer temperatures especially increase the abundance of black-legged ticks which expand their territories northward and survive through warmer winter seasons. Increases in tick borne illnesses, like Lyme disease and Anaplasmosis, are likely to occur due to a higher density of ticks in Vermont (Vermont Department of Health, 2018). Lyme disease is the most common tick-borne illness and in 2017, Vermont reported the highest number of probable cases in the U.S. There is an increased risk for tick bites in wooded areas and areas with tall grass and brush. These consequences may impact recreationists involved in outdoor activities such as hiking, camping, and mountain biking (Vermont Department of Health, 2018). Vermont has already seen an increase in Lyme disease cases over the recent years (Figure 7-8 shows probable and confirmed cases from 2005-2018).

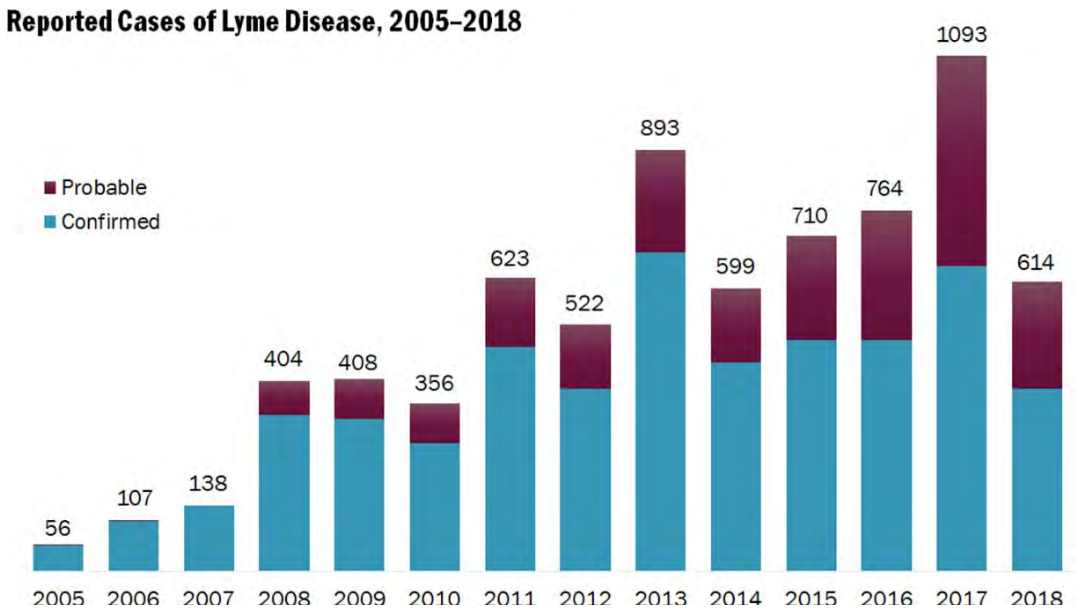


Figure 7-8: Vermont has had an increase in probable and confirmed cases of Lyme Disease in recent decades (Vermont Department of Health, 2018)

Shoulder seasons provide opportunities for lower-cost recreation opportunities. A warming climate allows activities that involve public spaces and minimal equipment, such as recreational birding and wildlife photography, two activities that are growing in participation nationally and can increase inclusion of many different demographics. Recreational birding is readily available through Vermont wildlife refuges, Audubon Vermont, and local interest groups. The 100-mile long Lake Champlain Birding Trail currently offers views of over 380 different species of birds and the state has over 4 million acres of important bird conservation areas (see Audubon Vermont at https://vt.audubon.org/). Along with birds, wildlife watching and photography are rising in popularity throughout the country (U.S. Fish and Wildlife Service, 2016). Wildlife photography is a relatively low-cost recreation opportunity that provides not only exciting on-site experiences, but like many recreation activities, memories that last a lifetime.

Overall, climate change in Vermont has the opportunity to lengthen shoulder seasons and provide a wider range of activities for recreationists to enjoy in warmer weather. The warmer weather also provides challenges, as it has major effects on Vermont's trees as well as its pest population, which has implications for recreation endeavors.

6.6 CONCLUSIONS

Climate change in Vermont will present distinct challenges and opportunities for the tourism and recreation industry. Currently, winter brings in the most money for the state with the prices and involvement costs of the ski industry. Downhill skiing will be available for recreationists for most of the twenty-first century, but Vermont will need to shift focus to the other seasons as the climate continues to warm. Other winter sports, such as Nordic skiing and snowmobiling, are more vulnerable to climate change and will probably be highly impacted by the changing climate. Pond hockey and skating outdoors on ponds will also face extreme challenges in the coming decades as ice-out dates occur earlier and ice thickness varies. As climate warms and the winter season inevitably gets shorter, the state needs to look for other ways to bring in revenue for warmer seasons.

Participation in warm-weather activities, such as water sports, hiking, mountain and road biking, and fishing will likely increase with warming temperatures and lengthened shoulder seasons. Increased use will require managers of warm weather recreation sites to be mindful of their resources and educate visitors with best-use practices in order to prevent trail erosion and water pollution. One promising aspect of recreation in the face of climate change would be the relative ease of summer sports. Less expensive gear is typically needed for summer recreational activities. Going for a hike in a state park is a cost-effective alternative to more expensive pursuits. Many summer outdoor recreation areas in Vermont do not charge for access, so anyone with means of transportation could visit. If Vermont continues to experience warming trends, the extended warm weather season bodes well for people of any financial background looking to spend time outside in our state. Managers of winter recreation sites, however, will need to continue to find creative ways to make money during the warmer months. Alternative forms of tourism and recreation, such as mountain biking, guided hiking tours, music festivals, and food and beverage events may offset some of the money lost from a shorter winter season; many of these solutions have been implemented by Vermont resorts in the past. Agritourism as well as other forms of food and beverage-related tourism also offer opportunities for Vermont to increase summer revenue, as Vermont continues to make a name for itself in the gastronomy world.

According to the State of Vermont Agency of Commerce and Community Development, Vermont receives over 13 million visitors each year. Many of these visitors participate in some sort of recreational activity during their stay in our state. Community leaders, business owners, and public land managers need to adapt to climate change swiftly and creatively for Vermont to continue to be a hub for recreationists across the globe.

6.7 ACKNOWLEDGEMENTS

We would like to thank Patricia Stokowski and David Kaufman for providing us with helpful feedback and guidance throughout our writing process. Additionally, we would like to thank the rest of our collaborators on the VCA, and Gillian Galford and Stephen Posner for aiding us in completing our chapter. We would also like to thank Tim Reiter, Chase Whiting, Abby Long, and the Staff in the Commissioner of Forests, Parks, and Recreation Michael Snyder’s office.

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7 HUMAN HEALTH

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7.1 KEY MESSAGES

- Climate change affects human health by exacerbating existing health problems and amplifying conditions for new health problems.
- Individuals who are children, over 65 years of age, of low socioeconomic status, Indigenous, or have previous health issues are more vulnerable to the health effects of climate change.
- Warmer and more moist temperatures in Vermont are likely to create more habitat for disease-carrying ticks and mosquitoes.
- Increases in the number and severity of natural disasters in Vermont will likely increase the risk of injury, illness, and death.
- Climate change could affect the quality and safety of food and water, which could lead to increases in food and water-borne illnesses.
- Decreases in air quality will exacerbate existing chronic diseases and decrease water quality.
- Mental health is inextricably linked with environmental health. Impacts from climate change could contribute to mental health challenges.

7.2 INTRODUCTION: CLIMATE CHANGE AND HEALTH

The myriad effects of climate change impact every part of the human body in one way or another, and climate change effects also disrupt health systems, supply chains, and health infrastructure (Salas et al., 2019; Lancet Countdown, 2020). Many changes are expected in Vermont, and all of these will have subsequent health impacts. For instance, increased heat waves, poor air quality days, and extreme weather lead to health-related impacts such as more emergency department (ED) visits, higher risk of respiratory illnesses, and increased occurrence of tick-borne diseases. Human health is, and will continue to be, detrimentally affected by the changes in climate (Figure 8-1). Particularly vulnerable populations to climate change are Vermonters sixty-five years and older, children under five years, pregnant women, Indigenous populations, and individuals in low-income communities (Melillo et al., 2014; USGCRP, 2018).

This chapter discusses: 1) climate change and how it will impact human health in Vermont; 2) how some demographics will be more vulnerable to these health impacts; and 3) actions we can take to lessen the impact. The many issues discussed in this chapter can be overwhelming in terms of number and types of actions, but readers should keep in mind that Vermonters can learn about and choose specific and individualized actions for each issue. In addition, the Vermont Climate and Health Program, a subset of the Vermont Department of Health, has many resources for further reading and information. Much of the data and information in this chapter is gleaned from the hard work of those who are part of that program.

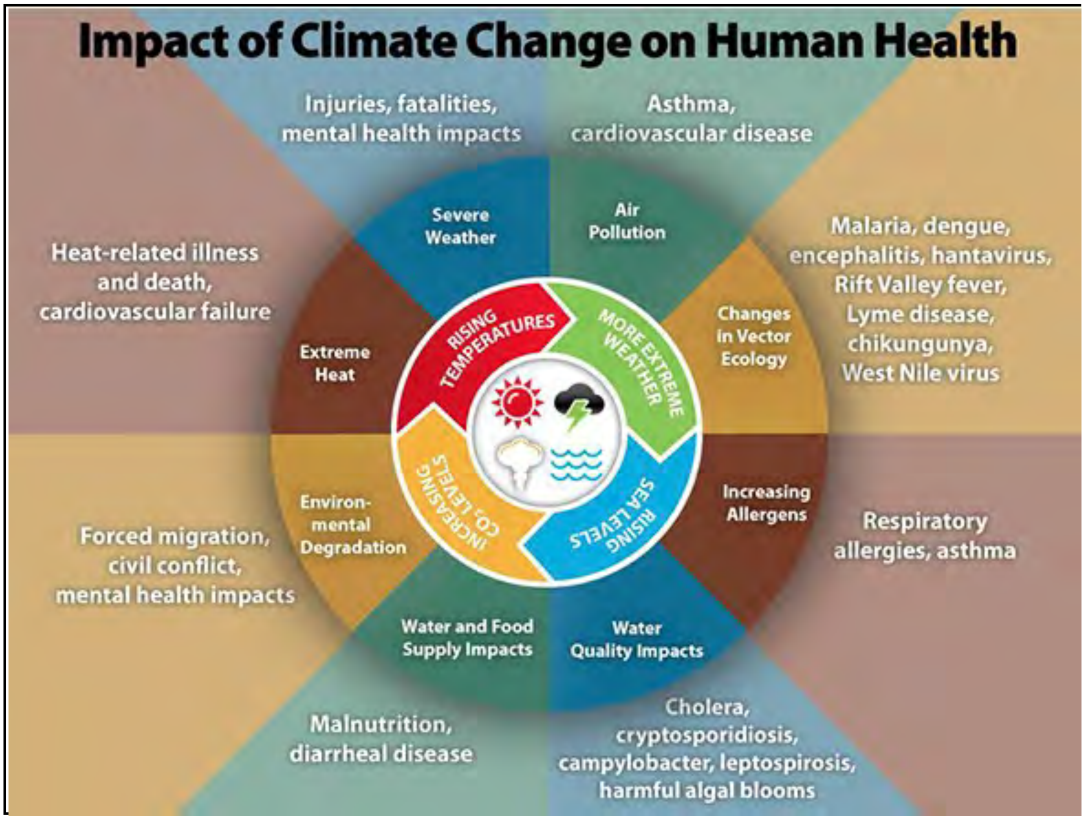


Figure 8-1: The impacts of climate change on human health (CDC, 2020b)

7.3 TEMPERATURE AND HUMAN HEALTH

Vermont, as a northern latitude state, experiences a wide range of temperatures throughout the year. The summers are warm and humid, and the winters are cold and dry. In the past, Vermonters generally have known what to expect from each season. However, in recent years, Vermont has begun to experience heat waves—prolonged abnormally high temperatures of several days or more—more frequently than ever before, as evidenced by three separate heat waves in the summer of 2020 alone (NOAA NWS Burlington, 2021). There has been an increase in the average annual minimum and maximum temperatures over time (see Climate Change in Vermont chapter), and these changes can have direct impacts on human health. Vermont already is seeing more heat stroke and dehydration from high temperatures and an associated increase in heat-related ED visits since 2003. With warming temperatures, the number of heat-related ED visits is expected to continue to rise, as discussed later in this chapter. In addition to an overall increase in temperature, other factors such as humidity, lack of wind, and physical exertion affect heat's impact on human health. These impacts can include heat exhaustion and heat stroke, dehydration, cramping, sunburn, heat rash, and more.

7.3.1 Changes in Temperature from Climate Change

One way to understand changes in temperature is to track the number of extreme heat days, defined as days over 90°F (32°C). Since the 1960s, Vermont has experienced an average increase of 0.5 days over 90°F (32°C) per decade (see Climate Change in Vermont chapter). Warm summer nights are more frequent as well, with a trend of 0.5 more nights per decade above 70°F since the 1990s resulting in a net gain of 1.5 more warm nights per year since the 1960s (Figure 8-2) (Galford et al., 2014). In addition, three of the ten heat waves since 2010 occurred in 2020 (Figure 8-3), and, as of this writing (August 2021), two heat waves have occurred so far in 2021 (NOAA NWS Burlington, 2021). Compared to an average of seven extreme heat days per year in the early 2000s, climate scientists predict that Vermont is likely to experience 15–20 extreme heat days each year by 2050 and 20–34 extreme heat days each year by 2100 (VT Dept. Health, 2016a).

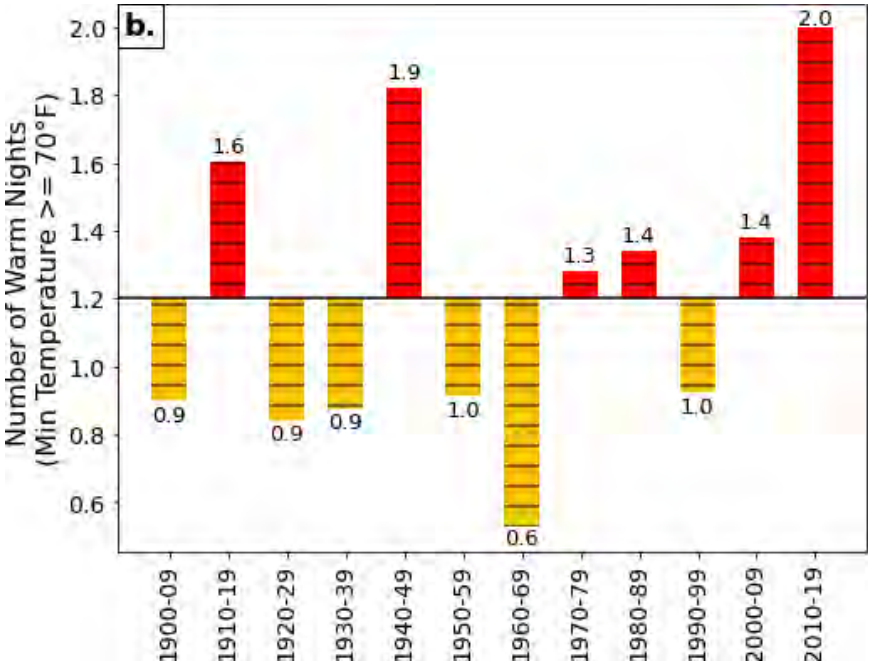


Figure 8-2: Number warm nights (days with minimum temperature above 70°F (horizontal hash marks)

Note: Decadal averages are plotted above and below the 1900–2019 mean value (solid black line). See Climate Change in Vermont chapter.

Jul 4-8, 2010	92	95	95	96				
Aug 31-Sep 3, 2010	92	92	91	92				
Jul 21-23, 2011	97	95	93					
Jul 12-15, 2012	91	93	93	90				
Jul 15-19, 2013	93	91	95	91	98			
Aug 17-20, 2015	90	91	90	91				
Sep 24-27, 2017	91	92	91	90				
Jun 30 – Jul 5, 2018	93	96	97	93	95	95		
Jun 18 – 23, 2020	92	91	94	94	96	96		
Jul 18 – 20, 2020	93	95	91					
Jul 26 – 28, 2020	92	93	91					
Jun 27-29, 2021	94	93	93					
Aug 24-26, 2021	90	90	94					

Figure 8-3: Of the ten heat waves from 2010–2021 in Vermont, three occurred in 2020 (NOAA NWS Burlington, 2021)

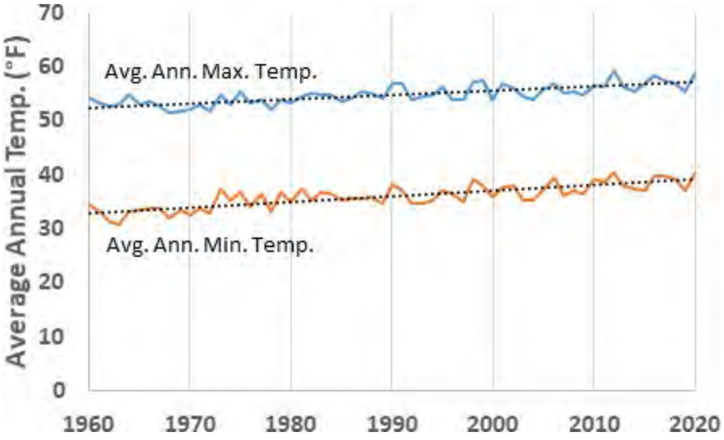


Figure 8-4: Average annual temperature (maximum and minimum) for the Burlington International Airport

Note: Across Vermont, the average maximum temperature has increased by 0.5°F per decade from 1991-2020, while the average annual minimum temperature has increased significantly by 0.7°F per decade over the same period (see Climate Change in Vermont chapter). (xmACIS, 2021).

While the increase in extreme heat days impacts Vermont summers, winters are also changing. The average minimum temperature in Vermont has increased by 2.6℉ (1.4°C) from the 1960s to the 2010s (Figure 8-4) (Galford et al., 2014; Vermont Emergency Management, 2018). This means that as the highest temperatures increase, so do the minimum temperatures. This impacts cold-weather crops, such as field corn, wheat, oats, blueberries, and apples, which experience lower yields as temperatures increase (Dunnington, 2010). Milk production also decreases when temperatures are above 75°F (24°C), as ideal milking temperatures range from 40°–75°F (4–24°C) (Dunnington, 2010). The potential decline in yields of these staple foods could lead not only to negative economic impacts, but also to food shortages and subsequent health impacts related to the lack of available food.

While the absolute amount of degree change in average temperature over time in Vermont may seem small, climate change will have surprising impacts on extreme weather, the growing season, precipitation, water and air quality, and more (VT ANR, 2021). Impacts secondary to extreme heat events are discussed below.

7.3.2 Impacts of Heat on Human Health and the Environment

Nationally, extreme heat is characterized by high heat and humidity and temperatures that exceed 90°F (32°C) for two to three days or more. Extreme heat is responsible for the highest number of annual deaths among all weather-related hazards (ready.gov, 2021). In Vermont extreme heat is considered 87°F (31°C) or higher. The health impacts of extreme heat can be very severe as the body works hard to maintain normal temperatures. Heat can have serious impacts on Vermonters' health, especially extreme heat (VT Dept. Health, 2016a). Vermonters are particularly at risk to extreme heat due in part to Vermonters' physiological adaptation to cooler climates. Such adaptation means that the threshold temperature above which mortality increases is lower than in warmer climates (Kovats & Hajat, 2008). When the human body cannot cool itself down properly, a person can be at risk for heat illnesses. Heat illnesses include strokes, cramps, fainting, heat exhaustion, and heat stroke, which is life-threatening. In addition, vulnerable Vermonters, such as those who are more exposed to hot conditions, those who are older or more sensitive to heat, and those who have limited resources, may be at a higher risk during heat waves, especially if they do not have means to cool down. Extreme heat can also exacerbate certain environmental conditions and pre-existing health conditions, rendering individuals more vulnerable to heat-related illnesses (VT Dept. Health, 2021c).

According to the Vermont Department of Health (VDH), Vermont is not uniformly impacted by heat waves; rather, “the highest risk areas for heat illness were located in the northeastern counties of Orleans and Essex, along with the urbanized areas of Bennington, Montpelier, Rutland, St. Albans, and Vergennes” (VT Dept. Health, 2016a). This disparity in risk can be seen in the VDH’s vulnerability index maps, where each district and/or county is rated on its vulnerability to climate change based on several different factors: population size, environmental factors, acclimatization ability, socioeconomic status, health status, and heat emergencies (VT Dept. Health, 2016c). Overall, the highest vulnerabilities exist in northeast and southwest Vermont (Figure 8-5). Essex and Orleans counties, located in the far northeast of the state, also have the lowest incomes, with average annual incomes approximately $7,000 and $9,000 less per capita than the state average (U.S. Census Bureau, 2019).

Many residents of the main cities in Vermont are at higher heat illness vulnerability to climate change than other residents in their counties. This is likely due to factors such as the age of the population (where vulnerable individuals are under five and over sixty-five years old) and environmental factors such as dense housing, high proportion of paved areas, and lack of tree cover (VT Dept. Health, 2016c).

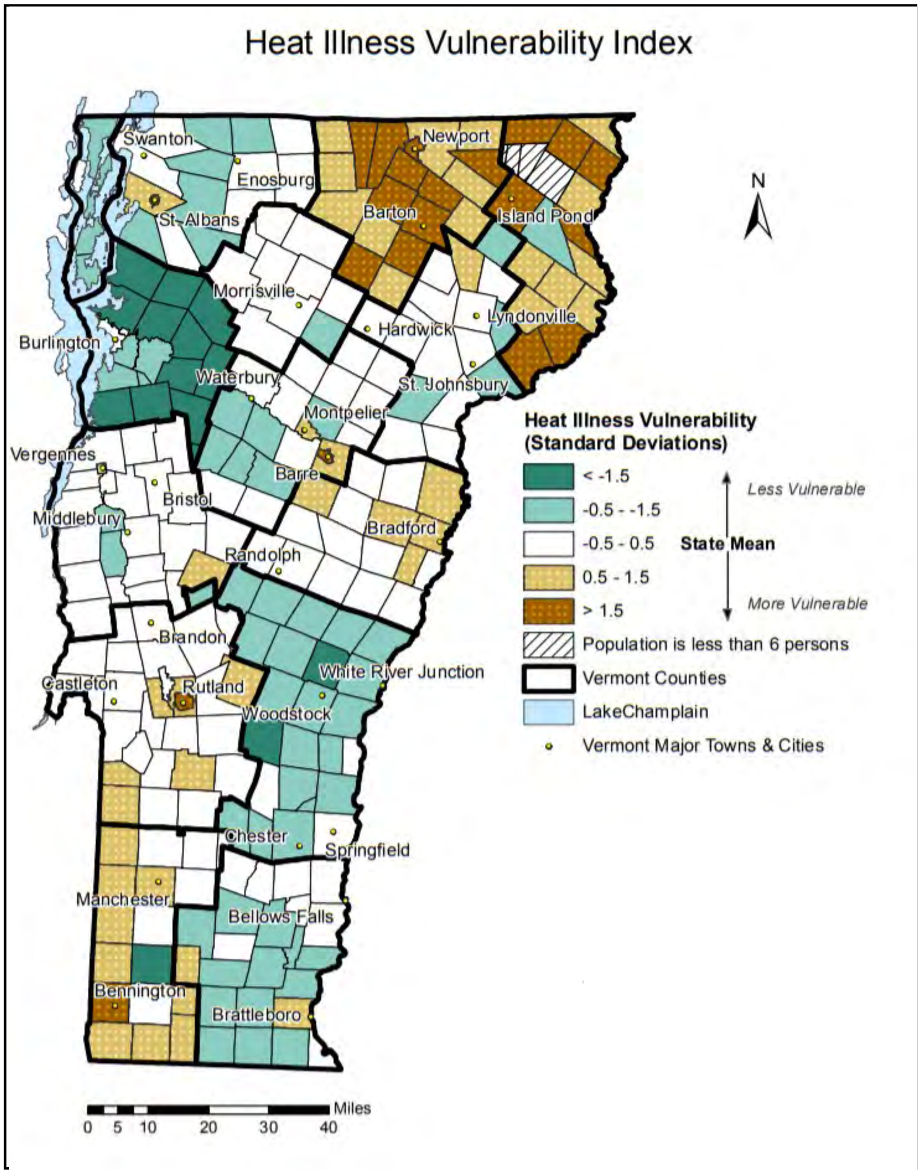


Figure 8-5: Heat illness vulnerability in Vermont

Note: Heat illness vulnerability in Vermont is based on town data, including population, environmental, acclimatization, socioeconomics, health, and heat emergency data (VT Dept. Health, 2016c).

Another indicator of the impact of extreme heat on health is the number of heat-related ED visits: ED visits “increase eight-fold when temperatures reach 87°F or higher” (VT Dept. Health, 2016a). The latest data on Vermonter’s ED visits from 2016 shows a general increase in overall visits since 2003 (Figure 8-6); this correlates with an increase in the number of extremely hot days, or days with temperatures greater than 90°F (32°C) (VT Dept. Health, 2016a, 2019b). In addition to heat stress, heat-related illnesses occur fifty times more frequently in urbanized areas in Vermont than in the peri-urban surrounding areas (VT Dept. Health, 2016a).

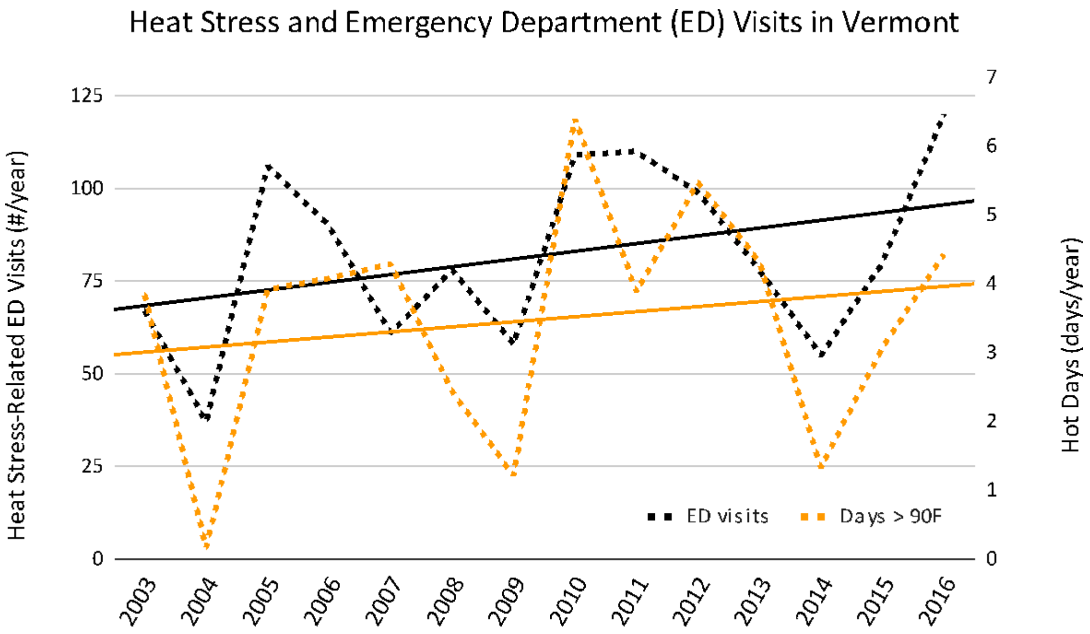


Figure 8-6: Number of emergency department visits due to heat stress by Vermonters (2003 - 2016, black dashed line with solid linear trend line) and number of days >90°F averaged across Vermont (orange dashed line with solid linear trend line).

Note: Emergency department visits (VT Dept. Health, 2019b) and number of days >90°F (Climate Change in Vermont chapter). E.D. visits include any Vermonter visiting an E.D. in Vermont, New Hampshire, New York for all years, and Massachusetts for all years except 2014, 2015, 2016.

Secondary Heat-Related Health Impacts

Another result of extreme heat is an increase in mosquito-borne illnesses because an increase in temperature prolongs ideal temperatures for mosquitoes that carry diseases to thrive (VT Dept. Health, 2018f). In other words, Vermont should expect more mosquito days. An increase in temperature and number of hot days in Vermont is likely to increase the number of people getting vector-borne diseases that already exist in Vermont and to create a climate favorable for other mosquito-borne illnesses to spread (VT Dept. Health, 2018f). This is discussed more in depth in the Vectors section of this chapter.

Higher temperatures also mean changes to the water systems in Vermont. In Lake Champlain, for instance, there are algal blooms that shut down public beaches and make the water hazardous to swim in each year. Cyanobacteria, commonly called blue-green algae, is found naturally in freshwater. However, with consistent hot weather, cyanobacteria can flourish and multiply to create a green scummy film over the top of a body of water; this is called a bloom (VT Dept. Health, 2018e). Cyanobacteria have toxins called cyanotoxins that, at high levels such as during an algal bloom, are a hazard to human health as they can cause stomach pain, diarrhea, liver damage, skin rashes, runny noses, and sore throats (VT Dept. Health, 2018e). This is discussed further in the "Food and Water" section of this chapter.

Heat events impact air quality and worsen air pollution. Heat waves create stagnant air that traps pollution particles that are then breathed in. Increased temperatures also increase the likelihood for drought, which dries out vegetation. This vegetation is then more susceptible to wildfire, which also releases pollutants into the air (Peterson et al., 2014). Vermont's growing season is lengthening (see Climate Change in Vermont and Agriculture and Food Systems chapters), which may impact the timing and duration of pollen (VT Dept. Health, 2018g). The combination of increased average temperatures and decreased air quality can change people's engagement in outdoor activities and recreation, which may be associated with increased rate of obesity and cardiovascular disease. Even with increased indoor exercise, people may have reduced access to restorative emotional benefits of time spent outside.

The impacts of increasing temperatures on air quality clearly have a myriad of health impacts. Worsening air quality exacerbates respiratory illnesses such as asthma and lung cancer, and, as seen above, can impact general cardiovascular health. These impacts are discussed further in the Air Quality section of this chapter.

7.3.3 Impacts of Cold on Human Health and the Environment

In Vermont, winter weather can cause icy roads and disrupt power supply, which in turn can lead to dangerous conditions such as car accidents and leaving Vermonters without heat. In addition, cold can lead to hypothermia and *frostbite*. Frostbite "is an injury caused by freezing of the skin and underlying tissues. First your skin becomes very cold and red, then numb, hard and pale. Frostbite is most common on the fingers, toes, nose, ears, cheeks, and chin. Exposed skin in cold, windy weather is most vulnerable to frostbite. But frostbite can occur on skin covered by gloves or other clothing" (Mayo Clinic, 2019). Shoveling snow can "stress [the] heart and lead to a heart attack" (VT Dept. Health, 2021e). An increase in minimum temperatures in Vermont may have the positive effect of potentially decreasing the number of cold-related illnesses and deaths, although by 2050 Vermont may experience more icy conditions (see Climate Change in Vermont chapter), which pose different risks. Any winter warming benefits could be outweighed by an increase in heat-related illnesses and deaths (Ebi & Mills, 2013). Further, warmer winters may bring less precipitation falling as snow and more as ice or lead to spring recreation on dangerously cold-water bodies.

7.3.4 What You Can Do

Individuals and Outdoor Workers

While extreme heat events can be detrimental to health, there are still many ways to reduce the impacts of extreme heat. For individuals working or recreating outside, it is a good idea to develop a safety plan to address extreme heat days (VT Dept. Health, 2021c). The Centers for Disease Control and Prevention (CDC) and the National Institute for Occupational Safety and Health (NIOSH) have guidelines that workers can follow to protect their health and safety during hot days (NIOSH, 2016). Some of these suggestions include: implement a buddy system to keep an eye on indicators of heat stress, provide and drink plenty of cool water, increase airflow of an area, implement a heat alert system for extreme heat days, take frequent rests in the shade, implement a heat-related training program, and train workers on heat-related first aid (NIOSH, 2016; VT Dept. Health, 2021c).

In addition, there are technological tools to aid in heat-related events. One of these tools is the Heat Safety Tool mobile app sponsored by the Occupational Safety and Health Administration (OSHA) and NIOSH. While the tool is aimed towards individuals who work outside, it can be beneficial for anyone who enjoys being outdoors in warm weather or is particularly vulnerable to the effects of extreme heat. OSHA uses the heat index to "calculate the heat index and get associated risk level worksite recommendations" (NIOSH, 2016). In other words, it helps workers and companies take the appropriate safety actions according to the heat, humidity, and wind factors at their workplace.

Cities and Communities

While it is important to respond to heat events on the individual level, acting as a community is also essential for community and individual well-being and health. Similar to creating a work safety plan, communities and cities can create community response plans that specify particular actions to take on extreme heat days (VT Dept. Health, 2021c). One such plan is the Vermont Hazard Mitigation Plan (Vermont Emergency Management, 2018), which discusses changes in temperature and ideas for mitigation. However, having individualized plans for specific communities can be extremely beneficial, as each community has its own needs and resources.

Communities can also open cooling centers. These centers can be "any air-conditioned building that can be opened to the public, such as a library, town hall, or senior center," (VT Dept. Health, 2021a). These centers include air conditioning, water access, seating, restrooms, and more, and can allow access to anyone (VT Dept. Health, 2021a). Along with cooling centers, communities can make sure to mobilize their care networks in order to make sure that those most vulnerable are being taken care of (VT Dept. Health, 2021a, 2021c).

Ensuring that buildings are energy-efficient is another action that communities can take to help reduce the impact of heat on human health (VT Dept. Health, 2021c). In addition, communities can encourage tree and shrub planting, thereby reducing the paved surface area that receives direct sun and contributes to urban areas being warmer than rural areas (Vermont Emergency Management, 2018; VT Dept. Health, 2021c, 2021a).

Homeowners and Landlords

Many of the above actions are short-term responses to heat events, not long-term actions. Homeowners and landlords can improve buildings to not only provide shelter from heat, but also improve the standards of living for many people at risk of heat illness. Homeowners and landlords may modify ventilation systems to increase flow of cool air, seal air leaks, weatherize the building properly, replace old lights with LED bulbs, install cooling devices such as air conditioners, and use light-colored construction materials to reflect light and heat (Hot Weather VDH, 2020). As mentioned previously, planting shrubs, vines, and trees can also be a longer-term solution to providing shade and preventing excessive urban heat (Vermont Emergency Management, 2018; VT Dept. Health, 2021c, 2021a).

7.3.5 Resources for Further Reading

1. Vermont Department of Health Heat Webpage (https://www.healthvermont.gov/health-environment/climate-health/hot-weather) (2021) provides detailed information about heat events in Vermont and actions individuals can take.
2. Vermont Department of Health Heat Vulnerability Index (http://healthvermont.gov/sites/default/files/documents/2016/12/ENV_EPHT_heat_vulnerability_in_VT_0.pdf) (2016) provides specific district-level information about vulnerability to heat in Vermont.
3. Heat Waves in Burlington, Vermont (https://www.weather.gov/media/btv/climo/extremes/heatwave.pdf) (2020) lists heat waves from 1886 to present.
4. Vermont Emergency Alert (https://vem.vermont.gov/vtalert) (2021) is where you can sign up to receive emergency alerts.
5. Vermont Hot Weather Media Toolkit (https://www.healthvermont.gov/sites/default/files/documents/pdf/ENV_CH_HotWeather_MediaToolkit.pdf) (2020) gives detailed information on heat changes in Vermont, the impacts, and the tools available for individual and collective action.

7.4 AIR QUALITY, POLLUTION, AND HEALTH IMPACTS

Climate change has a direct impact on air quality, as increased temperature and moisture levels in the atmosphere contribute to the distribution of allergens, pollutants, and irritants in the air (Dean & Green, 2018), and human activities simultaneously contribute to climate change and poor air quality (Figure 8-7). The WHO considers air pollution to be the "single largest environmental health risk" of climate change (Campbell-Lendrum & Prüss-Ustün, 2019; WHO, 2016), and the UN General Assembly ranked air quality as one of the top five major risk factors for human health (Figure 8-8) (Campbell-Lendrum & Prüss-Ustün, 2019). Approximately 9% of deaths are related to air quality issues (Ritchie & Roser, 2017; WHO, 2016) (see Fig. 7). Many noncommunicable diseases, such as asthma and chronic obstructive pulmonary disease (COPD), are exacerbated by poor air quality conditions.

Figure 8-7: Exhaust from vehicles contributes to air pollution, and thus decreases the quality of the air we breathe (Britannica, 2020)

Vermont is considered to have some of the cleanest air in the nation (VT DEC, 2021a). However, this does not mean that Vermont is immune to the impacts of pollution and aeroallergens, both of which affect the air we breathe. This air pollution can impact—or lead to—health conditions such as asthma, lung cancer, and heart disease (VT Dept. Health, 2021d). While, in general, Vermonters have not had to worry too much about air quality, there are certain climatic conditions that exacerbate air pollution (VT Dept. Health, 2021d). This section will discuss the types of air quality issues and the subsequent health impacts Vermont faces. It will also discuss the climatic changes likely to impact air quality, trends over time, and any changes to human health related to air quality. Finally, this section will discuss ways Vermonters can help reduce the impact of poor air quality on their health and work to improve Vermont's air in general.

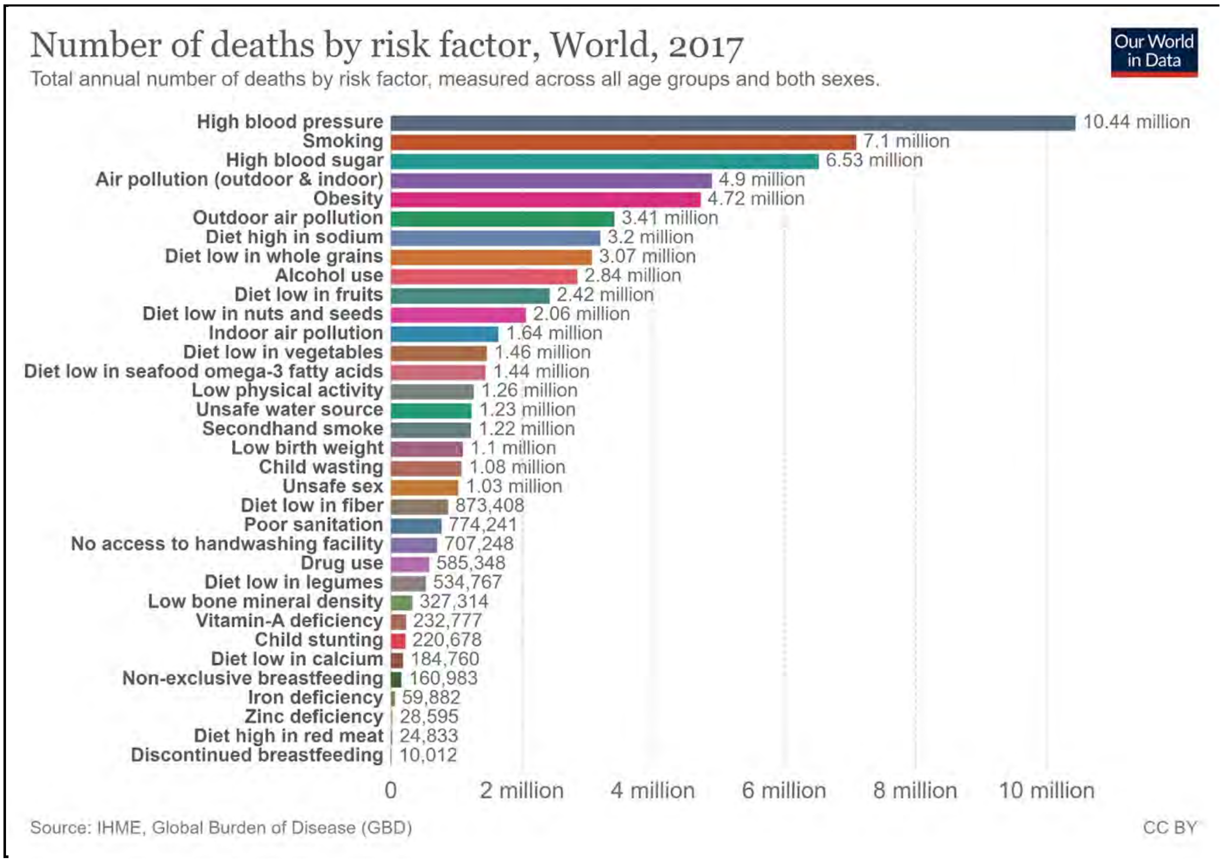


Figure 8-8: Air pollution as the fourth highest number of deaths by risk factor in 2017 (Ritchie & Roser, 2017)

7.4.1 Air Quality: Pollution and Allergens

There are two types of air quality indicators. The first is air quality impacted by pollution related to both indoor and outdoor human activity. The two types of air pollution that result from human activity and dominate air quality in the US are ozone (O3) and particle pollution (American Lung Association, 2021). Ozone is emitted from smokestacks, vehicle exhaust, and among other sources. At ground level, O3 creates smog, is very harmful to breathe in, and is "like getting a sunburn on your lungs" (American Lung Association, 2021). Particle pollution is a mix of very small solid and liquid particles in the air and comes from exhaust from vehicles and industry (American Lung Association, 2021). Particle pollution is deadly and can exacerbate pre-existing health conditions like asthma and COPD.

Vermont does not experience high volumes of traffic, nor does it have large amounts of industry contributing to air pollution (VT Dept. Health, 2021d). In fact, Burlington and South Burlington are ranked in the top four cleanest cities in the nation with regards to air pollution (American Lung Association, 2021). However, Vermont's air quality is impacted by pollution from outside of the state. For instance, in the summers of 2020 and 2021, the wildfires that ravaged California and western Canada produced enough smoke in the atmosphere that Vermonters could see a haze in the air from wildfire smoke for several days, an occurrence that is "far from the norm" (French, 2020). Therefore, while the state itself does not produce much pollution, it is not immune to the pollution from out of state. In addition, many Vermonters use wood as a source of heat for their homes; wood heat carries the risk of increased pollutants within the household. This pollution permeates the air we breathe, so we end up breathing in pollution particles, which can hurt our lungs and exacerbate pre-existing conditions like asthma. With the increase in hot days and precipitation that are anticipated with climate change, there is a likelihood that particle pollution and ozone episodes will be more frequent. In fact, temperature is the "most important meteorological factor in driving ozone episodes." So, with increasing temperatures, ozone pollution will likely be more prevalent (Shen et al., 2016).

The second air quality indicator is related to allergens. The number of warmer days and projected increase in carbon dioxide in the atmosphere lengthens the growing season for many plants in Vermont (Galford et al., 2014). An increase in plant growth releases more pollen and other allergens into the atmosphere (VT Dept. Health, 2018g). This increases the likelihood of pollen in the air, which impacts air quality (VT Dept. Health, 2019g). For instance, one common allergen that affects many people is ragweed, and ragweed is likely to benefit from climate change and expand its range in Vermont (Case & Stinson, 2018). An increase in allergens in the atmosphere impacts people with existing heart and lung conditions by lowering the quality of air that we breathe. Finally, climate change may result in more mold growth in homes, which also impacts air quality (VT Dept. Health, 2018g).

7.4.2 Air Quality and Health Impacts

Particle Pollution

Respiratory illnesses and allergies are greatly impacted by air quality. Poor air quality can lead to issues such as lung cancer, asthma, and heart disease (Figure 8-9; VT Dept. Health, 2021d). In 2019, the EPA concluded that particle pollution:

1. Causes early death from both long- and short-term exposure.
2. Causes cardiovascular damage, including heart attacks, heart disease, and strokes.
3. Likely worsens diseases such as asthma and COPD.
4. Likely causes cancer and nervous system harm, as well as developmental harm. (American Lung Association, 2021)

In 2013 and again in 2020, the EPA concluded that O3 exposure:

1. Causes worsening of pre-existing conditions like asthma and COPD.
2. Likely causes early death from both long- and short-term exposure.
3. Likely causes cardiovascular damage, including heart attacks, heart disease, and strokes.
4. May cause nervous system and reproductive and developmental harm. (American Lung Association, 2021; U.S. EPA, 2013, 2020).

As these conclusions indicate, air quality has a direct impact on several aspects of human health. Not only do air pollutants cause damage in and of themselves, but they also exacerbate pre-existing conditions like asthma.

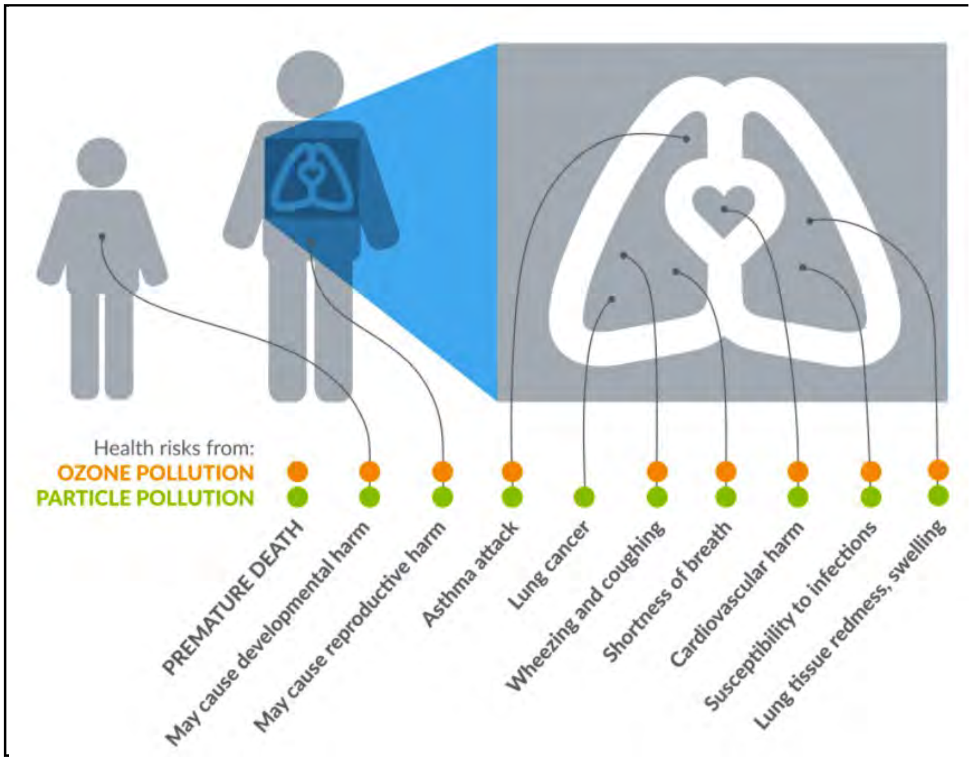


Figure 8-9: Impacts of ozone and particle pollution on human health (American Lung Association, 2021)

Aeroallergens

Climate change is lengthening the growing season in Vermont, and thus expanding the amount of time plants produce pollen and other such aero-allergens (VT Dept. Health, 2018g). The amount, concentration, and potency of pollen, spores, and other allergens in the atmosphere is thus increasing (K. R. Smith et al., 2014), triggering additional allergic responses and asthmatic reactions. Pollen and other aeroallergens can affect human health by creating itchy eyes, rashes, hives, runny noses, sinus issues, breathing problems, and more. One study showed that when there is a higher concentration of pollen in the atmosphere there are more ED visits due to asthmatic symptoms (Darrow et al., 2012). Thus, a longer growing season and increased plant growth due to increased carbon dioxide levels in the atmosphere from GHGs increases the likelihood of a longer aero-allergen season and a longer period of subsequent negative health effects. Another study found that over four million new childhood asthma cases could be attributable to nitrous oxide pollution, a pollutant in tailpipe emissions, industrial processes, and agricultural production (Achakulwisut et al., 2019). Urban centers host 64% of those cases.

Box 8.1: Ragweed

Ragweed is a common plant that provokes many allergic reactions (Figure 8-10). The pollen produced by this plant stimulates reactions like itchy eyes, sneezing, and even asthma. With increased temperatures and carbon dioxide (CO_2) levels in Vermont, there is likely to be an increase in ragweed flowering, duration, and pollen output (Stinson et al., 2016). One study warned that an increase in ragweed due to climatic changes in Vermont will necessitate monitoring and mitigating its presence and, since it grows primarily in disturbed soils, planning urban development and construction to minimize soil exposure and disturbance (Case & Stinson, 2018).

Figure 8-10: Ragweed (A. artemisiifolia) is a common allergen that may increase in flowering, duration and pollen with climate change) (Nonenmacher, R.A., 2014)

Asthma

Asthma is a prevalent chronic respiratory condition that is triggered by environmental factors such as pollen, particulate matter, fuel, and pesticides (VT Dept. Health, 2021d). Asthma impacts approximately 11% of Vermont adults (Figure 8-11) (VT Dept. Health, 2018g). The number of Vermonters with asthma increased about 50% from 2000 to 2010 (VT Dept. Health, 2018g). This rate in Vermont is higher than the national average, and one of the highest rates in the northeastern United States (VT Dept. Health, 2019g). Some experts think Vermont has such high asthma because of Vermont's older housing stock and lack of access to medical care due to the rural nature of the state (King, 2015). In addition, having pets is a trigger for asthma, and is a common link among those who have asthma in Vermont (King, 2015). During hot and humid days, more pollution (ozone and pollution particles) from vehicle emissions, wood smoke, and wildfires are trapped in the air and can exacerbate asthma (VT Dept. Health, 2019e, 2021d). Hot and humid days also can impact household mold, another trigger for asthma.

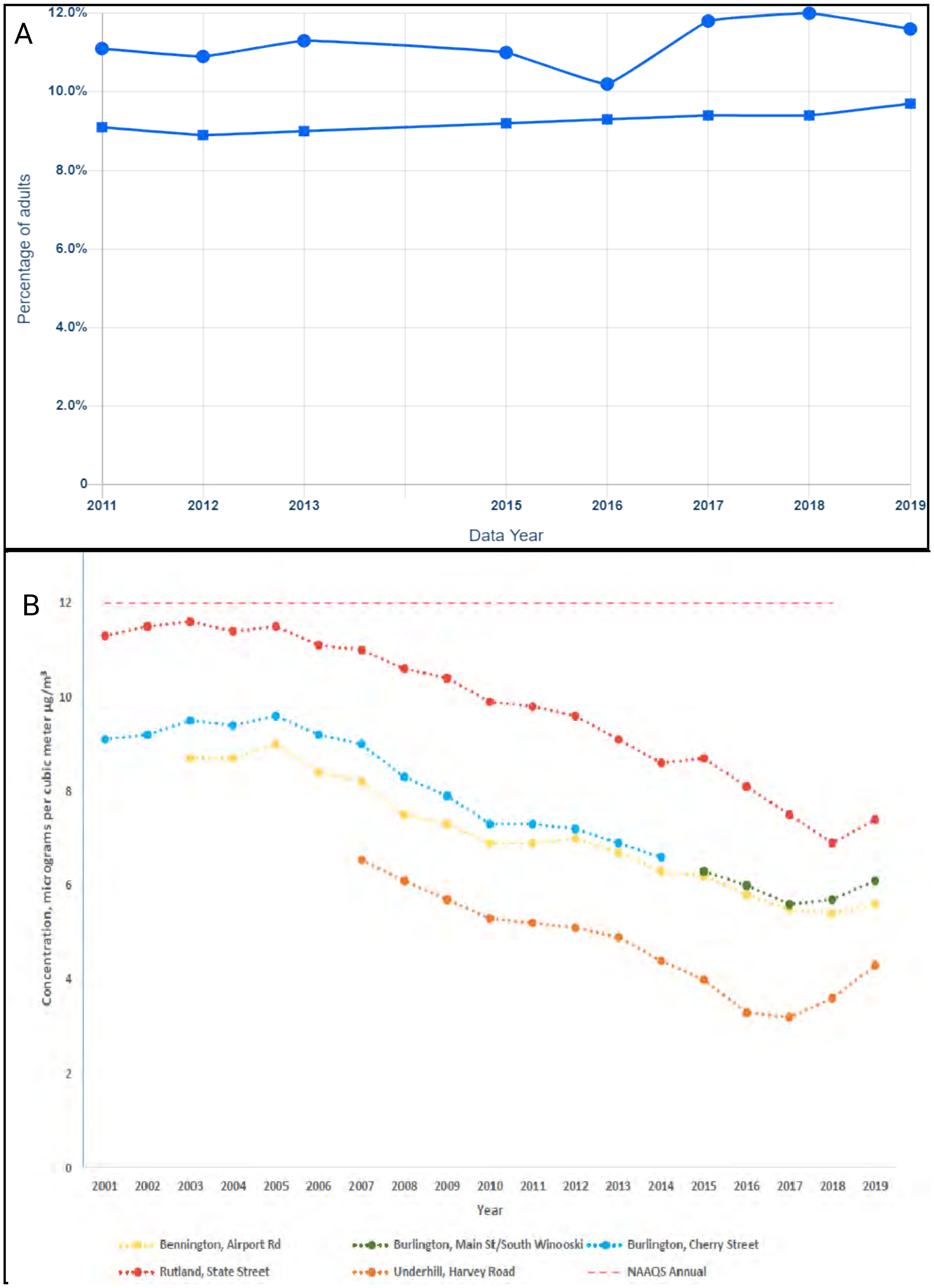


Figure 8-11: A. Asthma rates in Vermont (circles) and the U.S. (squares) B. Average annual fine particulate matter in the atmosphere

Note: Notice the spike in asthma rates in Vermont in 2016, just before an increase in particulate matter (Department of Environmental Conservation, 2021; United Health Foundation, 2021).

Asthma disproportionately affects people in lower socioeconomic groups. Among lower socioeconomic groups, the prevalence of asthma is 20%, compared to the statewide average of around 11% (VT Dept. Health, 2016b). This is due not only to potential environmental air quality factors, but also to increased risks of other comorbidities, low income housing, and smoking (VT Dept. Health, 2016b). A study in 2016 found that about four in ten lower income Vermonters were exposed to at least four or more negative environmental factors that exacerbate asthma (VT Dept. Health, 2016b). A state study found that smoking is almost twice as prevalent among Medicaid-insured Vermonters than other Vermonters, so these Vermonters and their families are more exposed to indoor smoke from cigarettes (VT Dept. Health, 2016b). This data points to socioeconomic disparities within Vermont that can be exacerbated by the burden of asthma, thus leading to even greater disparities.

Box 8.2: COVID-19 and Asthma

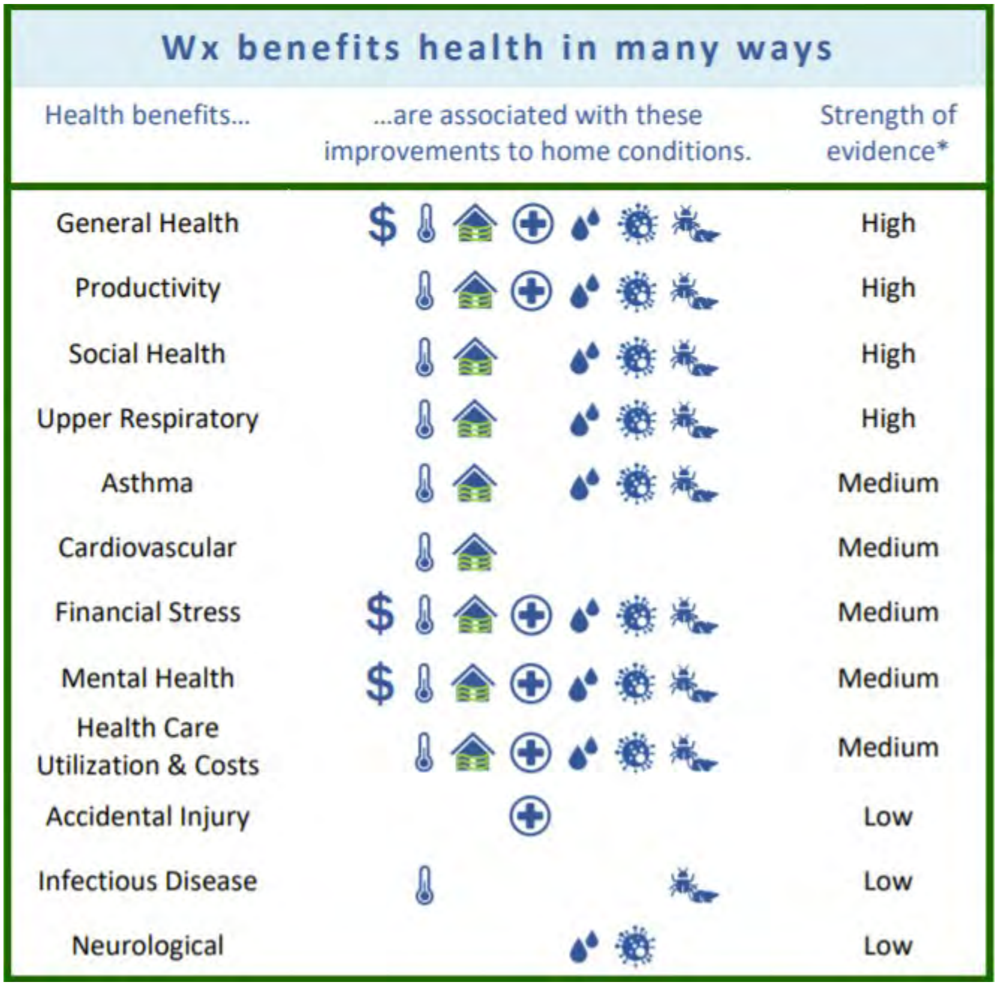
There is concern that individuals with asthma have increased risk of serious cases of COVID-19. Studies have shown that if asthma is well-managed, asthmatic individuals infected with COVID-19 have similar hospitalization rates as the general public (Terry et al., 2021). However, asthmatic individuals with moderate or severe asthma and are unable to manage their asthma are at a higher risk for hospitalization from a COVID-19 infection (CDC, 2021b). Because of the high rate of asthma in Vermont, the state has targets for decreasing and managing asthma in individuals. This would, in turn, help decrease the likelihood of hospitalizations from infections like COVID-19. The Respiratory Score Card indicates Vermont’s asthma goals and achievements (VT Dept. Health, 2019f).

7.4.3 What You Can Do

While air quality and air pollution are huge issues that are difficult to pinpoint or address singularly, Vermonters can take many actions to prevent poor air quality and thus address the subsequent health issues that arise.

Indoor Air Quality

There are three main factors to improving indoor air quality: improved ventilation, source control, and air cleaning (U.S. EPA, 2020). To act, Vermonters should examine sources of air pollution in the home (such as wood-burning stoves, gas stoves, old insulation, and moldy basements) and implement measures to address them, like cleaning wood stove chimneys, updating insulation, cleaning up mold, and making sure the home is well ventilated when using chemicals such as cleaning supplies. Installing carbon monoxide detectors or air filters also help with indoor air quality. To learn more about how to address these issues, go to the Vermont Department of Health's Healthy Homes webpage (Figure 8-12) (VT Dept. Health, 2021b).



Wx benefits health in many ways

Health benefits...	...are associated with these improvements to home conditions.	Strength of evidence*
General Health	$ 🌡 🏠 ⊕ 💧 🦠 🐜	High
Productivity	🌡 🏠 ⊕ 💧 🦠 🐜	High
Social Health	🌡 🏠 💧 🦠 🐜	High
Upper Respiratory	🌡 🏠 💧 🦠 🐜	High
Asthma	🌡 🏠 💧 🦠 🐜	Medium
Cardiovascular	🌡 🏠	Medium
Financial Stress	$ 🌡 🏠 ⊕ 💧 🦠 🐜	Medium
Mental Health	$ 🌡 🏠 ⊕ 💧 🦠 🐜	Medium
Health Care Utilization & Costs	🌡 🏠 ⊕ 💧 🦠 🐜	Medium
Accidental Injury	⊕	Low
Infectious Disease	🌡 🐜	Low
Neurological	💧 🦠	Low

Figure 8-12: The impact of weatherization ("Wx") on health (VT Dept. Health, 2018d)

Note: Weatherization includes methods of protecting a building from outside elements like sunlight, precipitation, cold, and heat.

Wood Burning

At 22 pounds of particulate matter emissions per capita, Vermonters burn wood at the highest rate in the nation (Associated Press, 2015; Mingle, 2019). Around one in six Vermonters rely primarily on wood to heat their houses (US EIA, 2020). Considered a renewable fuel source, wood burning is a component of Vermont's goal to be using 90% renewable energy by 2050 (VT Dept. Public Service, 2021). This includes the goal of increasing the percentage of Vermonters relying on wood fuel for heat from 21% to 35% by 2030 (Sherman et al., 2019).

Wood burning produces pollutant particles that can be inhaled and cause lung irritation, asthma attacks, and more (VT Dept. Health, 2017b). To reduce the impact of wood smoke on health, improving ventilation and filtration of the smoke is essential. Increasing the amount of outdoor air that circulates through the home (US EPA, 2014) and installing air purifiers, air monitors, and carbon monoxide detectors can help to reduce pollutants in the air and even detect when levels of wood smoke pollutants are high (VT Dept. Health, 2017b). In addition, because outdoor air quality tends to be poorer in the winter and at night, people who are sensitive to wood smoke should consider avoiding spending time outside when burning wood (VT Dept. Health, 2017b). The Vermont Department of Environmental Conservation suggests that Vermonters wishing to burn wood as a heat source in their homes have an energy expert assess the home and suggest efficient and clean wood stoves or boilers (VT DEC, 2021a). For instance, automated wood pellet heating greatly reduces the emissions emitted by wood burning while also effectively heating the home. State incentives, community outreach, and partnerships may help individuals make the transition to wood pellet burning and also adopt other alternative energies in their homes (Edling & Danks, 2021).

In the Home

There are many ways to reduce emissions and pollutants in the house. One is by using LED bulbs, which last longer and use less energy. Another way is by using energy-efficient appliances. They use less energy, which ultimately reduces the amount of pollutants emitted (VT DEC, 2021a). Efficiency Vermont is a good resource for learning about appliances and methods of improving your home's energy use. Making sure that appliances are up to date and in good working order (i.e., by replacing filters, updating heating systems) helps with efficiency, too. Using cleaning products that are citrus-based and paints that are water-based latex ultimately help to reduce the number of irritants in your household. In addition, starting fires with natural starters, such as charcoal chimney starters, helps to reduce the amount of pollutants emitted in the home (VT DEC, 2021a).

Outdoor Air Quality

Reducing pollutants in outdoor air improves the air we breathe. When it comes to pollution in the air outside, some factors are out of our control, such as pollution swept in from neighboring areas. However, there are many things that Vermonters can do to improve local outdoor air quality, reduce emissions that contribute to greenhouse gas (GHG) emissions, and ultimately mitigate climate change. By doing these actions, Vermonters are not only protecting their health and the health of those they care for, but also helping Vermont meet its GHG reduction goals.

Travelling

Transportation is the largest contributor to GHG emissions in Vermont, which impacts climate change and the air we breathe (Figure 8-13) (Bureau of Transportation Statistics, 2017). While we rely heavily on fossil fuel-powered vehicles to get from one place to another, there are several ways to travel and reduce vehicle exhaust emissions. One is to ride a bike. This has the dual benefit of reducing GHG emissions and improving individual health through exercise. Public transportation is another option, as is carpooling. While the latter two options emit GHGs into the atmosphere, sharing transportation reduces total GHG emissions and thus reduces the amount of pollution in the air. Vermont has several resources related to public transport and signing up to carpool with others.

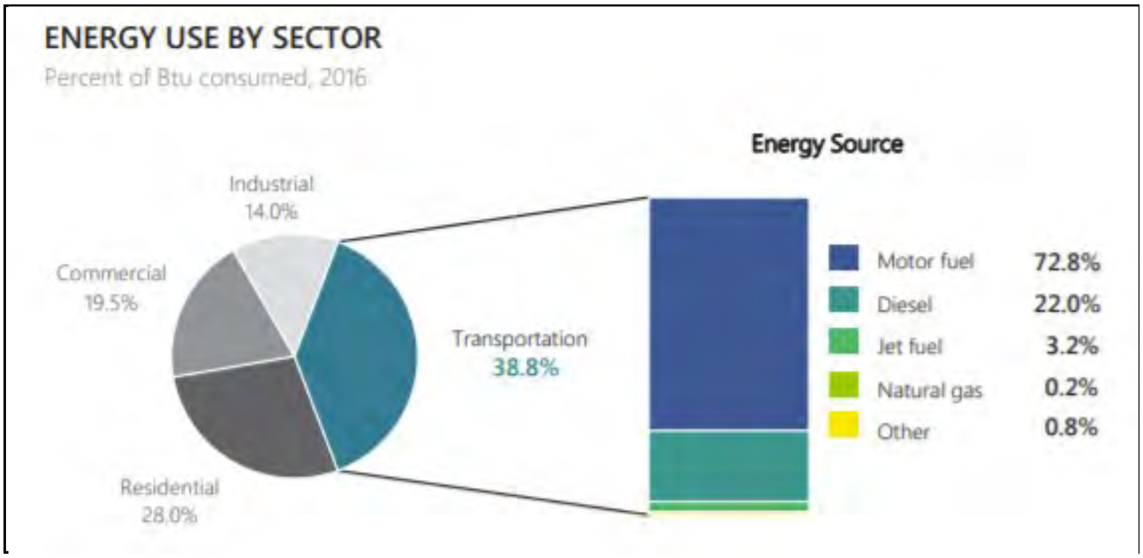


Figure 8-13: Energy use by sector in Vermont in 2016

Note: The transportation consumes the most energy (in Btu—British Thermal Units) in Vermont. By walking, carpooling, and taking public transport, Vermonters can contribute to decreasing these numbers (Bureau of Transportation Statistics, 2017).

If it is necessary to use a car, the Vermont Department of Environmental Conservation suggests that people connect with others to share rides, limit idling in the car, and ensure your vehicle is up to date on maintenance (VT DEC, 2021g). In addition, keeping car tires fully inflated helps reduce gas usage, and avoiding topping up on gas can help prevent gas spillage (VT DEC, 2021g). Finally, switching to an electric or fuel-efficient vehicle has the multiple benefits of reducing emissions while conserving energy and saving you money. In Vermont, there are several incentives from the state, utilities companies, federal government, etc., to switch to electric vehicles (EVs) (Drive Electric Vermont, 2021). Drive Electric Vermont has more information on these incentives, including a calculator. Not only do these interventions help to improve air quality, they also help Vermont achieve its goal to reduce GHG levels to 40% below 1990 levels (State of Vermont, 2021b). Because personal transportation (i.e., cars, motorcycles, trucks) makes up about 45% of Vermont's total GHG emissions, cutting down on driving can make a huge impact on GHG reduction and air quality (State of Vermont, 2021b).

Recreating

Before exercising outside, consider checking the air quality index and the allergen forecast. Air quality can also be found via TV, radio, and newspapers. When pollution levels are high, avoid exercising outside. In addition, try to exercise away from busy roads or in high traffic areas, as these areas tend to have higher concentrations of pollutants from vehicles (American Lung Association, 2021).

7.5 EXTREME WEATHER EVENTS

Extreme weather events—heat, storms, floods, and heavy rainfall, which are becoming more severe and frequent in the Northeast, including Vermont—increase the risk of injury, illness, and death (K. R. Smith et al., 2014; USGCRP, 2018). Precipitation events and flooding are the extreme weather events that pose the largest public health threat in Vermont. Hurricanes and tropical storms increasingly threaten the state, as seen by the devastation caused by Tropical Storm Irene on August 28, 2011 (Figure 8-14). Irene caused record flooding and severe damage to Vermont's landscape, infrastructure, and economy, and it caused six deaths and many more direct and indirect physical injuries (VT Dept. Health, 2017a). The destruction caused by Irene to transportation infrastructure alone totaled $250 million, according to VTrans (National Wildlife Federation, 2016). Irene exemplified the risks of extreme weather events and brought climate change resilience conversations to the forefront for legislative and planning agendas in the state (Hewitt, 2016). This section will discuss the changes in extreme weather events in Vermont, the impacts of those events on human health, and actions Vermonters can take to address these issues.

Figure 8-14: Devastated infrastructure due to Tropical Storm Irene in Killington, VT (Inside Climate News, 2016)

7.5.1 Changes in extreme weather events

This section describes previous extreme weather events and examines the impacts of climate change on extreme weather events in Vermont. Vermont has experienced eighteen nationally declared disasters from 2010 to 2020, compared with eleven from 2000 to 2010 and twelve from 1990 to 2000 (Figure 8-15) (FEMA, 2021).

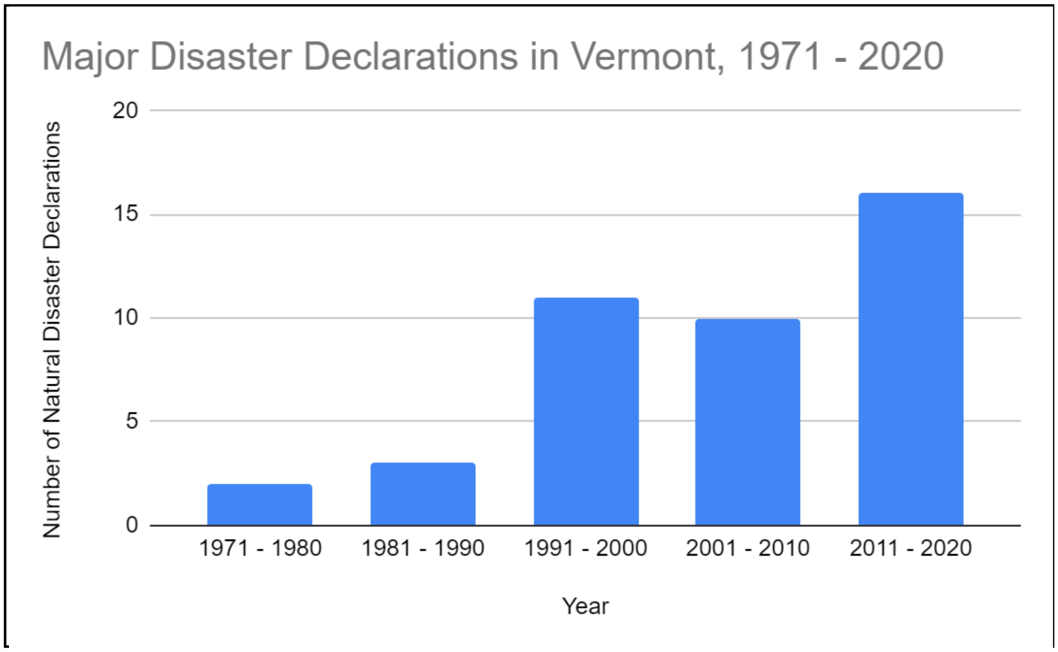


Figure 8-15: Number of nationally declared disasters in Vermont 1971-2020 (FEMA, 2021)

Note: Disasters include severe storms, precipitation, flooding, high winds, landslides, and freezes.

Precipitation

Vermont is getting wetter (Figure 8-16) (See the Climate Change in Vermont chapter). Since 1965, Vermont has seen an increase of seven inches in annual precipitation, and almost double the amount of precipitation days per year (VT Dept. Health, 2017a). In addition, Vermont is likely to see an increase in winter and spring precipitation, which initially will fall as snow, but increasingly will fall as winter rain (Galford et al., 2014) (see Climate Change in Vermont chapter). These changes have cascading effects on agriculture, plants, and human health, as will be discussed later.

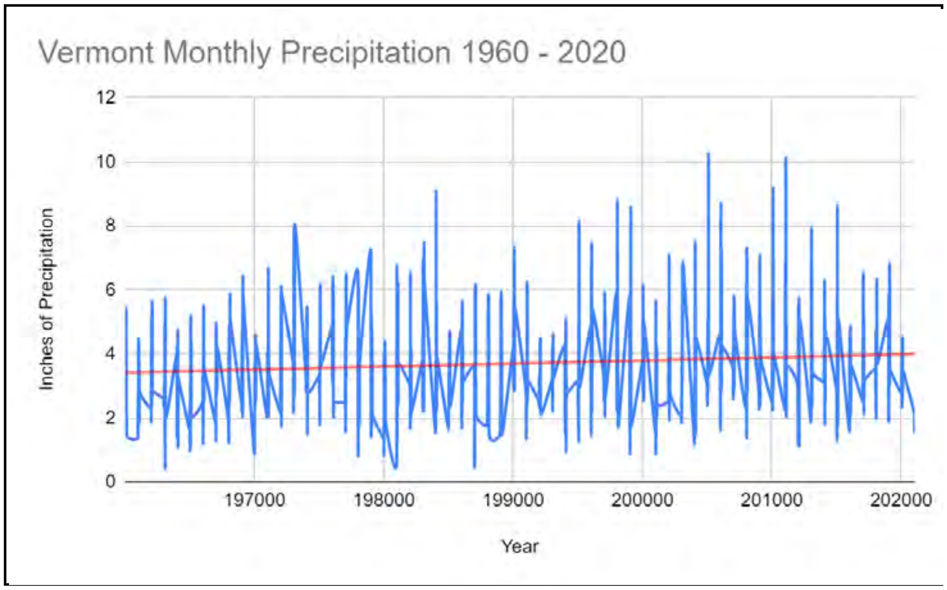


Figure 8-16: Annual precipitation in Vermont 1960–2020 (blue lines). Average precipitation (red line) is increasing. (NOAA National Centers for Environmental Information, 2021).

Increased precipitation increases the potential for floods. Floods can destroy roads needed to transport people to the hospital and other health centers. Floods can cause physical injuries and death and can damage critical infrastructure. Vermont is prone to flooding from its rivers and streams and from storms like Tropical Storm Irene. During that storm, the changes to stream size were massive. Kevin Geiger of the Two Rivers Ottauquechee Regional Commission said, “There [were] streams that [weren’t] streams — streams that had no water in them (before the storm) — that split houses in half. You had streams you could step over carrying full-size trees” (State of Vermont, 2021a).

7.5.2 Impacts on health

Extreme weather events impact human health directly and indirectly from environmental and infrastructural damage.

Increased precipitation will create ideal growing conditions for household mold in buildings that are prone to dampness. As mentioned in the Air Quality section, mold can have serious impacts on respiratory health. In addition to exacerbating or causing respiratory issues (such as asthma, COPD, and allergies), long-term, low-level exposure to mold can cause fatigue, depression, concentration issues, and low immune responses (American Lung Association, 2021).

Damaged critical infrastructure—such as electricity, refrigeration, health care, and sanitation and water treatment—causes health risks. These include heat or cold issues from power outages, illness from spoiled food or water contamination, and mental health issues such as post-traumatic stress disorder (PTSD)(VT Dept. Health, 2017a; Wang et al., 2019). In addition, damaged infrastructure can disrupt medical treatment, especially problematic for those with chronic illnesses (see Box 8.3).

PTSD, anxiety, depression, and exacerbation of existing mental health issues are common during and after severe storms, such as Tropical Storm Irene (Wang et al., 2019). For instance, in town meetings in the town of Rochester immediately after Tropical Storm Irene, first one, then nine, then twenty-five residents were identified as needing urgent medical care or support for both mental and physical ailments (Shulins, 2014). When interviewed three years after the storm, multiple residents reported long-term emotional disturbances including anxiety, sadness, fear, and stress (Buschman et al., 2014).

BOX 8.3: Rebuilding Mental Health Support After Tropical Storm Irene

The mental health impacts of Tropical Storm Irene persisted much longer than it took to rebuild much of the devastated infrastructure. After the destruction wreaked by Irene, including the damage of Vermont’s main mental health facility in Waterbury, the state had to scramble to provide mental health services and support to those impacted (Buschman et al., 2014). Irene brought to the forefront major issues within Vermont’s centralized mental health system, and Vermont has since restructured much of its mental health delivery to be based more on community-support than hospitalization (Hewitt, 2016). The storm catalyzed a state-level response to change the existing system to support individuals and fostered a strengthening of community closeness, support, and pride (Buschman et al., 2014).

Risks of infectious diseases increase with increased precipitation and storms, especially when people are exposed to overrun sewage systems and have skin wounds (REF: Rudolph & Harrison, 2016). An increase in vector-borne diseases (see Vectors section) is also possible, as often there is an increase in mosquitoes, and thus an increase in the risk of those mosquitoes carrying disease, after heavy storms and precipitation (REF: Rudolph & Harrison, 2016). While in Vermont there are now very few mosquito-borne illnesses, with increased temperatures and precipitation that is likely to change (see Vectors section).

7.5.3 What You Can Do

While extreme weather events can be devastating, there are things that individuals, communities, and the state can do to plan for them and reduce their impact. For more information on community resilience, see the Community Development chapter.

Infrastructure Improvement

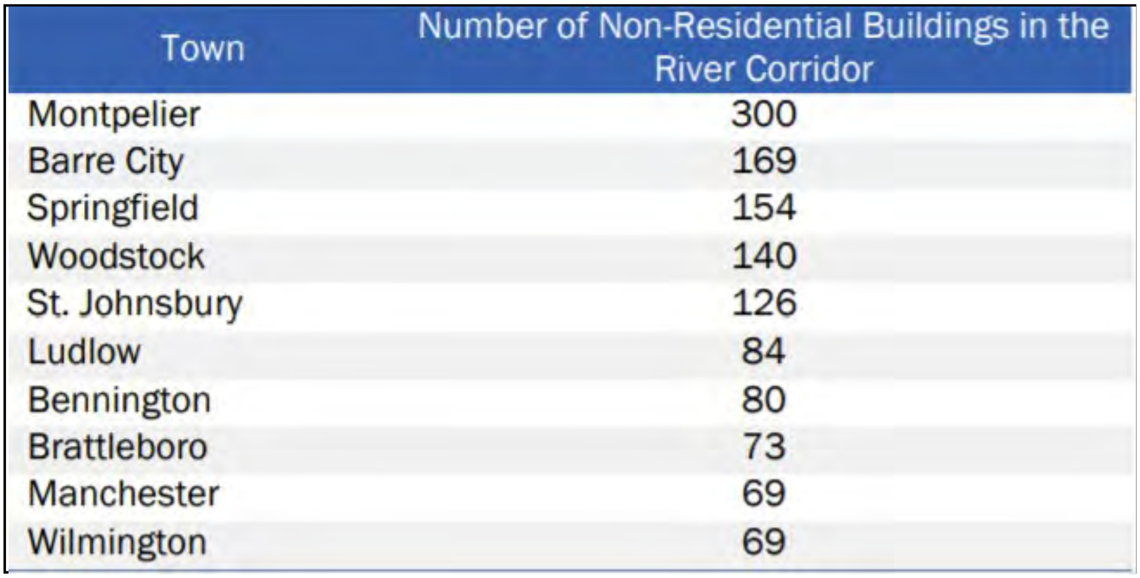
Vermont has notoriously old infrastructure. In 2019, Vermont received a C letter grade for its infrastructure by the American Society of Civil Engineers (ASCE), with particularly bad grades for stormwater and wastewater infrastructure (both of which received a D+) (American Society of Civil Engineers Vermont Section, 2019). Old infrastructure leads to health risks, including air quality problems and physical danger from unsafe structures. When roads, buildings, bridges, and other infrastructure are not up to standards, they are more easily damaged by storms like Irene. This issue requires a multi-pronged solution that focuses on leadership, investment, and resilience at the state and federal levels. The ASCE suggests Congress fully fund infrastructure programs and fix the Highway Trust Fund (American Society of Civil Engineers Vermont Section, 2019). It also suggests that leadership focus on leveraging proven and emerging technologies to bolster infrastructure projects, make use of limited resources, scale up the use of natural or “green” infrastructure to enhance the resilience of various infrastructure sectors, and inventory state stormwater assets (American Society of Civil Engineers Vermont Section, 2019).

In Vermont, green infrastructure partnerships like the Green Infrastructure Collaborative aim to maintain and enhance the natural and environmental spaces within communities and cities. These partnerships emphasize the essential roles that natural spaces play in various sectors of society (e.g. increasing property values, rendering ecological services, and promoting human health and well-being) (VT DEC, 2021b). As previously mentioned, having tree cover within urban areas helps reduce the impact of extreme heat on health. In order to preserve these spaces, Vermonters can join the conversation, sign up for listservs, and volunteer to plant trees or other green infrastructure initiatives through Vermont Urban and Community Forestry's webpage (https://vtcommunityforestry.org/programs) (VT UCF, 2021).

To learn more about green infrastructure, visit Vermont Urban and Community Forestry's paper (https://vtcommunityforestry.org/sites/default/files/pictures/Resource/greeninfrastructure.pdf) on green infrastructure's roots and applications (VPIC, 2012). See also the green infrastructure section of the Community Development chapter.

Community Hazard Mitigation Planning

Risk Assessment: Understanding the risks that communities face is an important tool in planning for how to respond to these potential risks. One tool created after Tropical Storm Irene by Flood Ready Vermont is the Vermont Flood Ready Atlas (https://floodready.vermont.gov/assessment/vt_floodready_atlas) (State of Vermont, 2021c), which overlays information on flood hazard areas on a map in order to visualize places at risk of flooding. This mapping tool helps to identify communities and residences that are within flood-prone areas in Vermont. Second, as of 2015, approximately 90% of Vermont's communities participate in the National Flood Insurance Plan (NFIP), which insures buildings and communities in case of flooding (State of Vermont, 2021c). Yet another tool to assess communities' status on flood preparedness and resilience is also from Flood Ready Vermont: community hazard reports. These reports are updated by communities around Vermont to assess: the level of flood risk, the status of certain infrastructure and the status of local mitigation action plans (State of Vermont, 2021c). According to the Vermont Economic Resilience Initiative (VERI), thirty-four towns were identified as economic centers that have high infrastructural and non-residential vulnerability to flooding. The ten towns with the most buildings in river corridors are listed in Figure 8-17 (VT Dept. Housing and Community Development, 2015).



Town	Number of Non-Residential Buildings in the River Corridor
Montpelier	300
Barre City	169
Springfield	154
Woodstock	140
St. Johnsbury	126
Ludlow	84
Bennington	80
Brattleboro	73
Manchester	69
Wilmington	69

Figure 8-17: Ten towns with the most buildings that are at-risk of flooding (VT Dept. Housing and Community Development, 2015)

Hazard Mitigation Planning: In 2018, the Vermont Division of Emergency Management, in partnership with other state agencies, released an updated Vermont State Hazard Mitigation Plan, which outlines plans to reduce the impacts or risks of natural hazards (VT Emergency Management, 2018). The Plan discusses how to mitigate the impacts of natural hazards, not how to mitigate the events themselves (Figure 8-18) (VT Emergency Management, 2018).

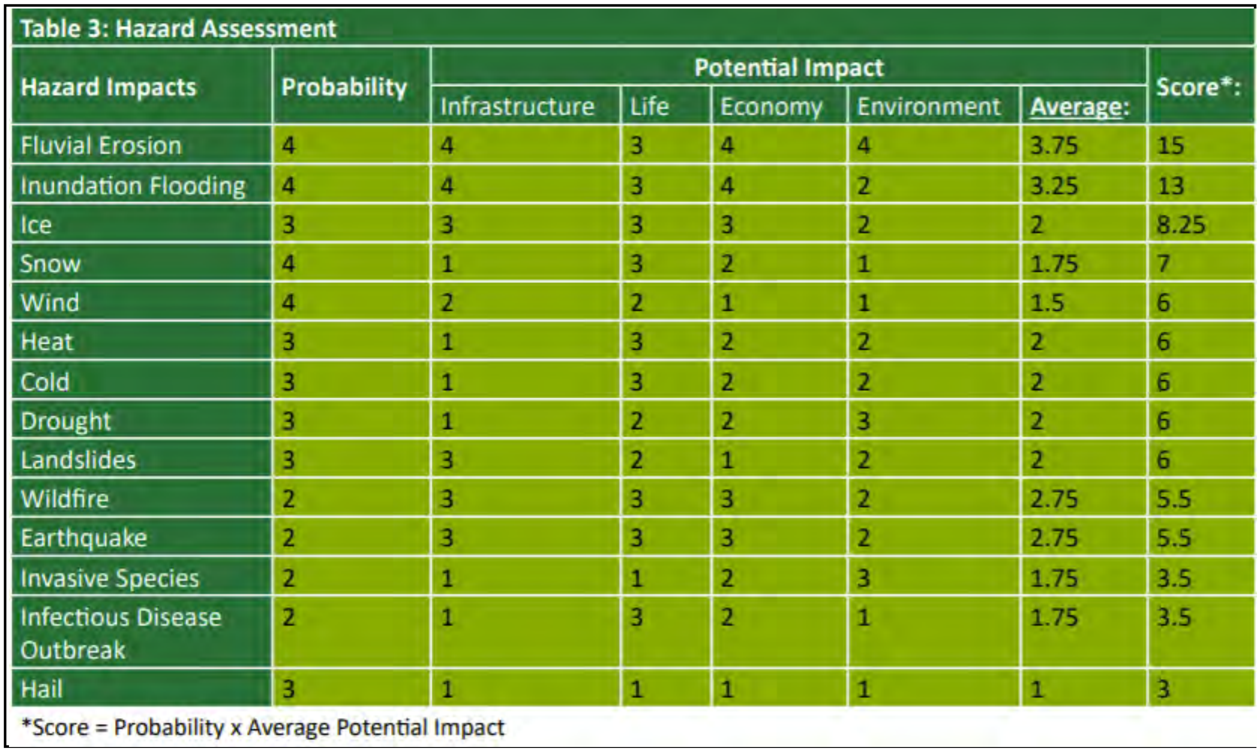


Table 3: Hazard Assessment

Hazard Impacts	Probability	Potential Impact					Score*:
		Infrastructure	Life	Economy	Environment	Average:	
Fluvial Erosion	4	4	3	4	4	3.75	15
Inundation Flooding	4	4	3	4	2	3.25	13
Ice	3	3	3	3	2	2	8.25
Snow	4	1	3	2	1	1.75	7
Wind	4	2	2	1	1	1.5	6
Heat	3	1	3	2	2	2	6
Cold	3	1	3	2	2	2	6
Drought	3	1	2	2	3	2	6
Landslides	3	3	2	1	2	2	6
Wildfire	2	3	3	3	2	2.75	5.5
Earthquake	2	3	3	3	2	2.75	5.5
Invasive Species	2	1	1	2	3	1.75	3.5
Infectious Disease Outbreak	2	1	3	2	1	1.75	3.5
Hail	3	1	1	1	1	1	3

*Score = Probability x Average Potential Impact

Figure 8-18: Assessment of probable impact of hazards in Vermont on various sectors of society

Note: Hazards listed are the current and past hazards, and probability indicates the likelihood of experiencing that hazard the future. The rankings of 1-4 under Probability and Potential Impact sections indicate frequency of occurrence, with 1 being unlikely and 4 being highly likely. Vermont continues to be at risk mostly from erosion, floods, ice, snow, and wind (VT Emergency Management, 2018).

The Plan also discusses different mitigation and actions, including Hazard Mitigation Assistance, public assistance programs, and the Emergency Relief and Assistance Fund (ERAF), which provide a degree of disaster insurance to those at risk from natural disasters. Planning for the disaster eventualities allows towns and municipalities in Vermont to understand the risks and make sure there are plans and actionable items to enact in case of a natural disaster. As of September 2018, Vermont had 173 approved Local Hazard Mitigation Plans (LHMPs), constituting 63.7% of the state's plans, 50 expired LHMPs, and 52 municipalities without any approved LHMP (Figure 8-19) (VT Emergency Management, 2018). Ensuring that all municipalities in Vermont have current LHMPs will help the state with regards to hazard mitigation.

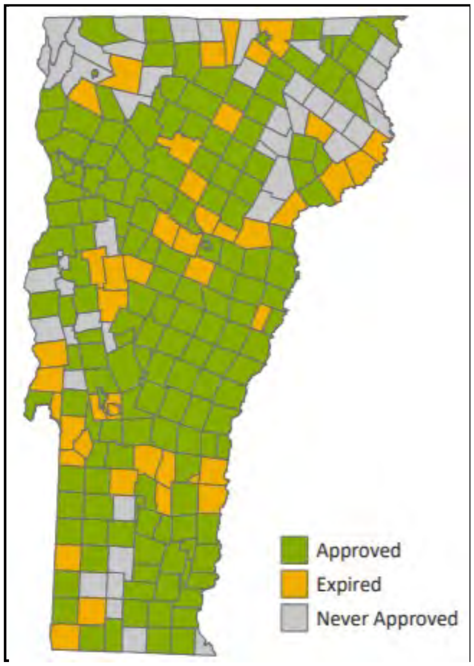


Figure 8-19: Status of municipal Local Hazard Mitigation Plans in Vermont in 2018 (VT Emergency Management, 2018)

Community members can engage with the local hazard mitigation chapter, sign up for VT Alerts, and keep up-to-date on local hazard mitigation plans to keep abreast of how Vermont and its local communities are reacting to and preparing for future hazards.

Box 8.4: Starting Over Strong Vermont

After Tropical Storm Irene damaged or destroyed many residential homes and much state infrastructure, many people were left without access to crisis support. Enter Starting Over Strong (SOS) Vermont, a federally funded organization that deploys small teams of crisis support workers to communities impacted by crises and provides psycho-educational support and short-term interventions to struggling individuals and families struggling. SOS Vermont hosted community gatherings to promote the creation of support groups, to build resilience, or just to share stories. SOS Vermont is an excellent example of a short-term, post-disaster intervention that helps individuals and communities recover after disasters (Aikman, 2012).

7.6 VECTORS

Climate change is increasing the spread of vector-borne diseases across the United States and around the world (Githeko et al., 2000; Rocklöv & Dubrow, 2020; K. R. Smith et al., 2014). Briefly, warmer temperatures are more ideal environments for organisms such as mosquitoes and ticks, insects that can spread diseases like malaria, Lyme, chikungunya, Zika, etc. (Rocklöv & Dubrow, 2020). Because Vermont is likely to experience a warmer environment as the climate changes, there is likely to be an increase in the diseases spread by vectors. This section will discuss the changes in vector ecology (study of disease-bearing organisms) and tick-borne and mosquito-borne diseases, how Vermonters are impacted by these changes, and what Vermonters can do to address these changes.

Vector-borne diseases are particularly responsive to climate change for several reasons (Figure 8-20). Climate change may shift the geographic range where the vector may live; reduce natural controls (such as die-off caused by winter freezing) on vectors and hosts; influence the life cycle of a pathogen; or affect the incubation time of a pathogen within its vector, leading to an increase in reproductive and biting rates (Patz, 2003; Patz et al., 1996, 2000; Patz & Frumkin, 2016; USGCRP, 2018). Hotter summers and warmer winters will allow tick-borne diseases, such as Lyme disease, Anaplasmosis, and Babesiosis, to flourish. Other vector-borne diseases, such as West Nile Virus and Eastern Equine Encephalitis, will also increase. All these factors lead to an increased risk of contracting a vector-borne disease, especially for populations already living in or near the geographic area where the diseases are present (K. R. Smith et al., 2014). Monitoring and controlling vectors like ticks and mosquitoes in Vermont will become an extremely important task as the climate continues to warm.

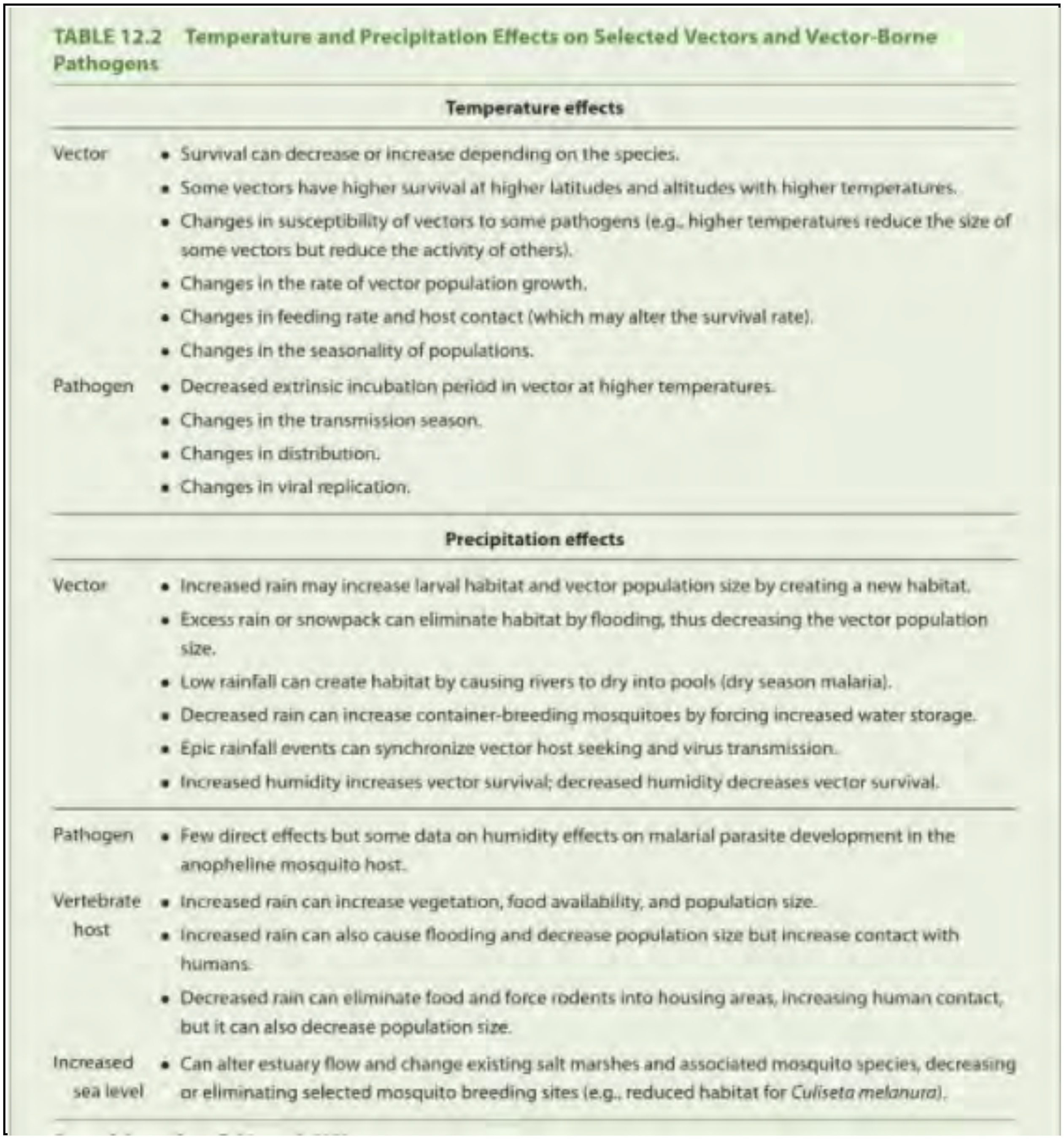


TABLE 12.2 Temperature and Precipitation Effects on Selected Vectors and Vector-Borne Pathogens

	Temperature effects
Vector	• Survival can decrease or increase depending on the species. • Some vectors have higher survival at higher latitudes and altitudes with higher temperatures. • Changes in susceptibility of vectors to some pathogens (e.g., higher temperatures reduce the size of some vectors but reduce the activity of others). • Changes in the rate of vector population growth. • Changes in feeding rate and host contact (which may alter the survival rate). • Changes in the seasonality of populations.
Pathogen	• Decreased extrinsic incubation period in vector at higher temperatures. • Changes in the transmission season. • Changes in distribution. • Changes in viral replication.
	Precipitation effects
Vector	• Increased rain may increase larval habitat and vector population size by creating a new habitat. • Excess rain or snowpack can eliminate habitat by flooding, thus decreasing the vector population size. • Low rainfall can create habitat by causing rivers to dry into pools (dry season malaria). • Decreased rain can increase container-breeding mosquitoes by forcing increased water storage. • Epic rainfall events can synchronize vector host seeking and virus transmission. • Increased humidity increases vector survival; decreased humidity decreases vector survival.
Pathogen	• Few direct effects but some data on humidity effects on malarial parasite development in the anopheline mosquito host.
Vertebrate host	• Increased rain can increase vegetation, food availability, and population size. • Increased rain can also cause flooding and decrease population size but increase contact with humans. • Decreased rain can eliminate food and force rodents into housing areas, increasing human contact, but it can also decrease population size.
Increased sea level	• Can alter estuary flow and change existing salt marshes and associated mosquito species, decreasing or eliminating selected mosquito breeding sites (e.g., reduced habitat for *Culiseta melanura*).

Figure 8-20: Temperature and precipitation effects on vectors and pathogens (Table 12.2, Patz & Frumkin, 2016)

7.6.1 Tick-Borne Diseases

Tick-borne diseases are increasing in Vermont (Allen et al., 2019). Climate change has expanded the areas where ticks live and breed, and thus the areas where disease occurs.

Diseases from vectors such as ticks that have not been seen in Vermont will start to become prevalent, and those that are already here will become more pervasive. In Vermont, tick-borne diseases are generally most prevalent in southern counties, but the trend could move northward with climate change. Longer summers not only could change vector distribution and biology, but also could lengthen the prime transmission period for these diseases (Figure 8-21). The Vermont Department of Health states succinctly:

> *Ticks can only live in areas where the climate is suitable for them, having the right temperature and the right amount of moisture. Warming temperatures due to climate change, especially during the winter months, may make Vermont more hospitable to blacklegged ticks. Warmer winters can also help the survival of important hosts for ticks, like white-footed mice. This could result in tick populations increasing in areas where they are already present, and the introduction of ticks to areas that were not previously infested, such as colder, northern areas and areas at higher elevations [...] Ticks are typically not active at temperatures below freezing. Warming temperatures due to climate change mean more days when ticks are active and looking for blood meals, which means a greater risk of ticks biting people. (VT Dept. Health, 2018c).*

Additionally, ticks prefer warm, moist weather, which is likely to become more prevalent in New England as global temperatures increase (Polhamus, 2017). In Vermont, there are fourteen known types of ticks, four of which carry disease. The most abundant is the blacklegged tick, or deer tick, which is responsible for over 99% of all tick-related diseases, including Lyme, babesiosis, and anaplasmosis (VT Agency of Agriculture, Food and Markets, 2021b; VT Dept. Health, 2018c). The spread of tick-borne diseases depends on three factors: how many ticks are in the area, how many ticks are infected, and how often people encounter those ticks (VT Dept. Health, 2018c).

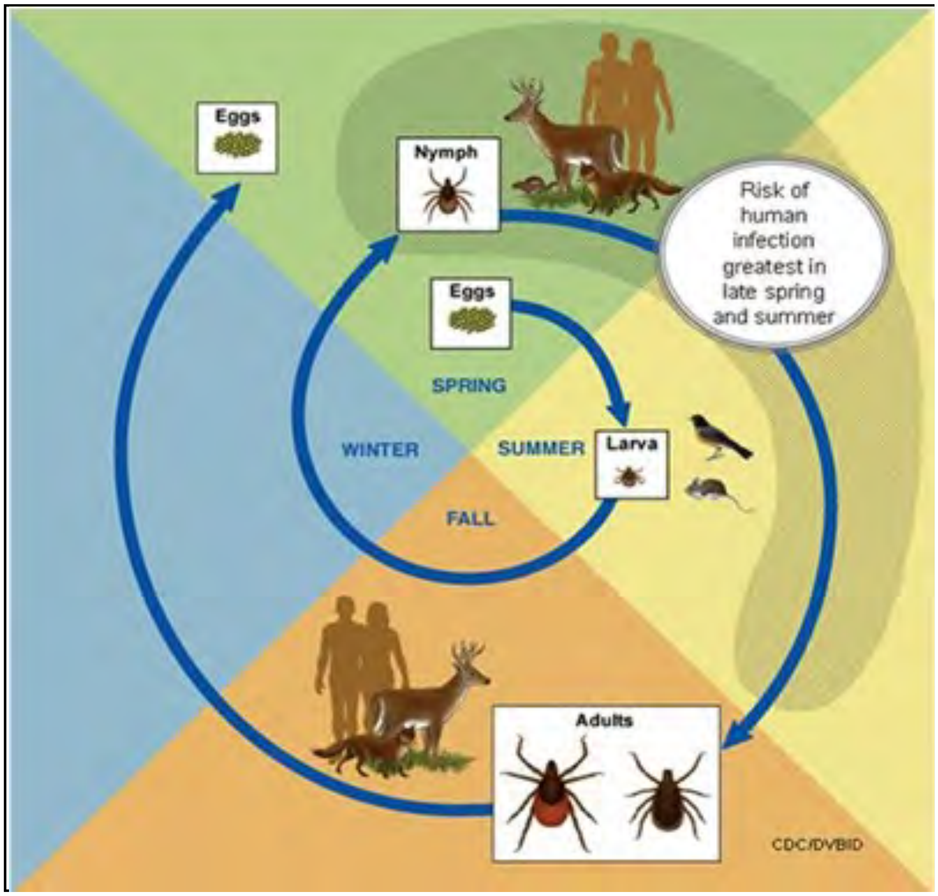


Figure 8-21: Life cycle of ticks and tick-borne illnesses

Note: Eggs are laid in the spring, larvae hatch in the summer, nymphs emerge the following spring and summer, and adults emerge in the fall and following spring (VT Agency of Agriculture, Food and Markets, 2021b).

Lyme Disease

The most common tick-borne disease in Vermont, Lyme disease is caused by the *Borrelia burgdorferi* bacterium, which is spread to humans through the bite of the blacklegged tick (VT Dept. Health, 2019c). First described in the 1970s, the number of cases of Lyme disease in the United States has more than doubled since 1997 and has significantly increased since 2005 (see Figure 8-22) (Allen et al., 2019; Dumic & Severnini, 2018; Patz & Frumkin, 2016; VT Dept. Health, 2018c). In addition, there has been a shift in geography of Lyme disease northward, impacting states like Vermont at higher rates (Allen et al., 2019). In 2017, Vermont had the highest rates of Lyme in the country: 1,093 confirmed and probable cases, as compared to 138 cases just a decade before in 2007 (VT Dept. Health, 2018c).

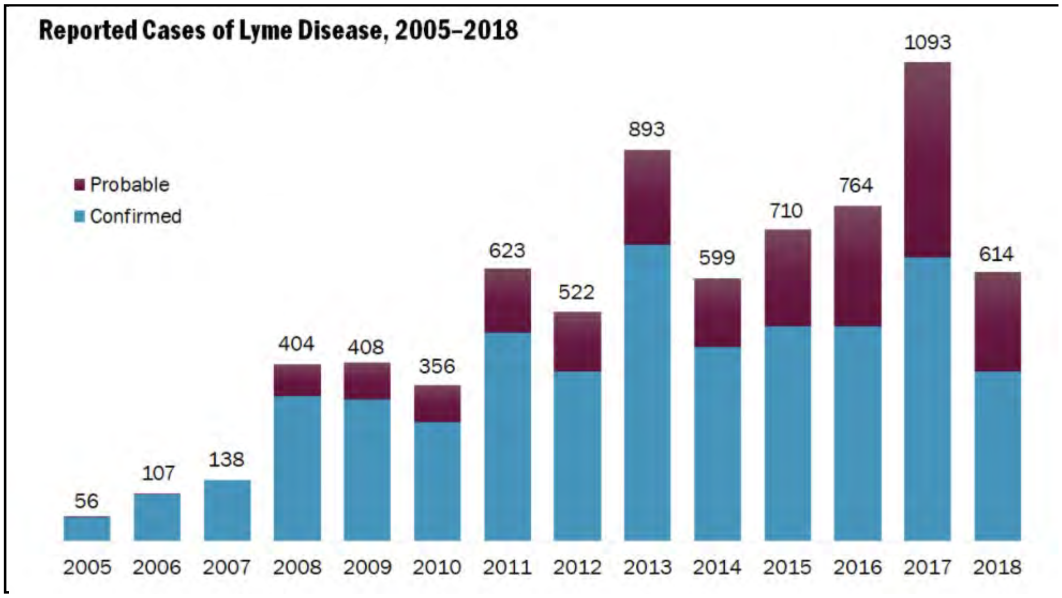


Figure 8-22: Number of reported cases of Lyme disease 2005–2018 (VT Dept. Health, 2018c)

A study of ticks and tick-borne illnesses in Vermont in 2018 found that over half the female ticks collected and tested were positive for the Lyme disease bacterium (Figure 8-23). In addition, a study of the incidence of Lyme by country in the period 2005–2018 showed that Bennington, Windham, Rutland, and Windsor counties in southern Vermont had the highest incidences of Lyme in 2018 (Figure 8-24) (VT Dept. Health, 2018c). Cases have drastically increased since 2005. While the study indicates prevalence in southern counties, Lyme disease now has occurred in all counties in Vermont.

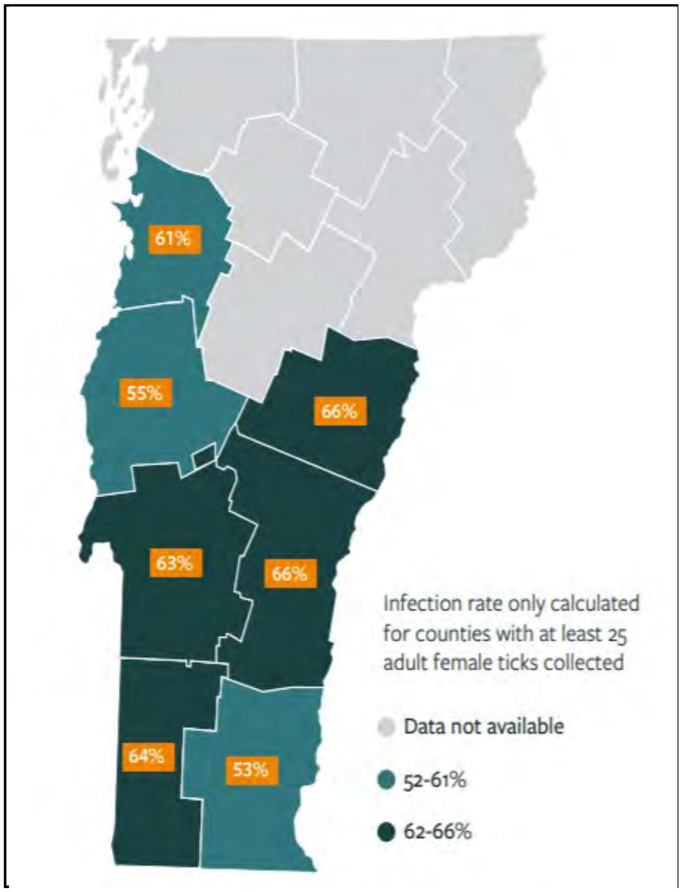


Figure 8-23: Percentage of female ticks testing positive for the Lyme disease pathogen B. burgdorferi in 2018 (VT Dept. Health, 2018c)

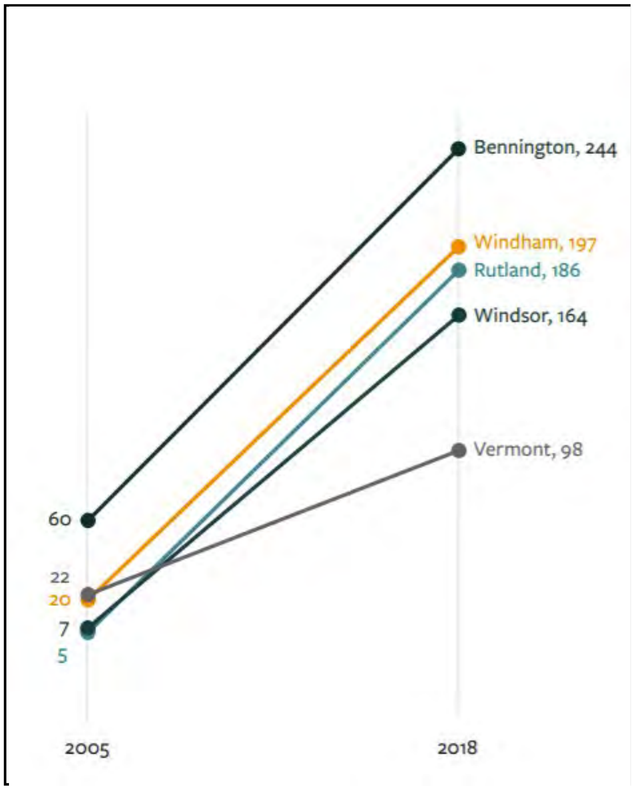


Figure 8-24: Lyme disease incidence for the four counties with the highest incidence and statewide in Vermont (per 100,000 population) in 2005 and 2018 (VT Dept. Health, 2018c)

Symptoms of Lyme disease often include fever, chills, muscle pain, joint pain, headache, fatigue, and the Erythema migrans skin rash (CDC, 2018). This rash often appears at the site of the tick bite and gradually expands, forming a bullseye appearance. If not treated, the infection can spread to joints, the heart, and the nervous system. Lyme can be diagnosed by a healthcare provider based on symptoms, physical examination, the possibility of exposure to infected ticks, and laboratory tests. If diagnosed in a timely manner, most cases of Lyme disease can be successfully treated with antibiotics (VT Dept. Health, 2019c).

Anaplasmosis

Like Lyme disease, anaplasmosis is transmitted by the blacklegged tick; it is the second most common tick-borne illness in Vermont (VT Dept. Health, 2018c). Anaplasmosis is caused by the bacterium, *Anaplamsa phagocytophilium*. Incidence of the illness has increased drastically since 2008: three cases were reported in 2008, almost 400 cases were reported in 2017, and 244 cases reported in 2018 (Figure 8-25) (VT Dept. Health, 2019c). The illness has been reported throughout Vermont, but in 2018 over 30% of cases occurred in Bennington County (Figure 8-26) (VT Dept. Health, 2018c). Anaplasmosis occurs more commonly in older Vermonters, and more often in males than in females (VT Dept. Health, 2018c). Everyone is at risk for contracting anaplasmosis, from spring to autumn.

Symptoms of anaplasmosis include, fever, chills, headache, myalgia, nausea, vomiting, diarrhea, loss of appetite, cough, and, in rare cases, a rash (CDC, 2018). Anaplasmosis is generally treated by antibiotics.

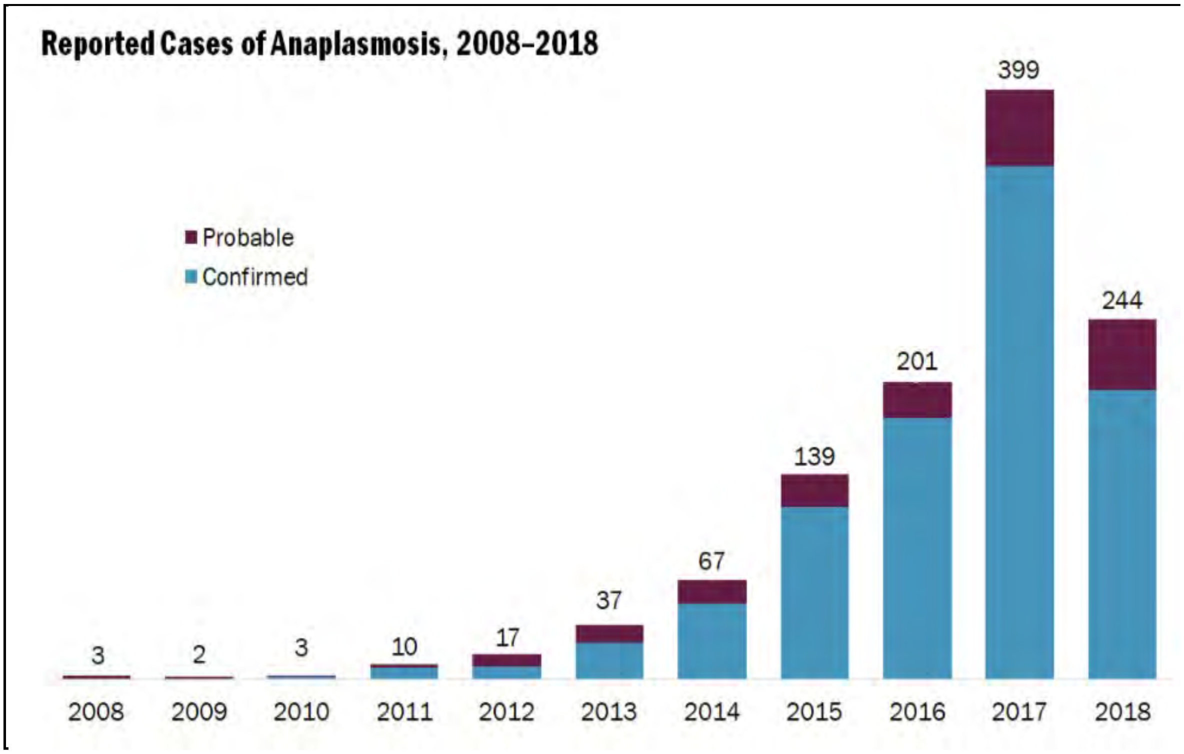


Figure 8-25: Reported cases of anaplasmosis 2008–2018 (VT Dept. Health, 2018c)

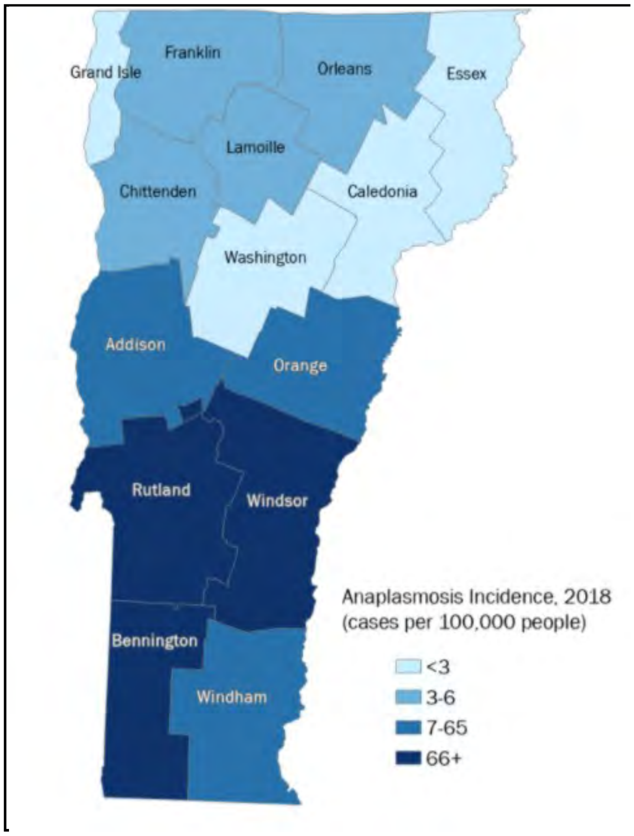


Figure 8-26: Anaplasmosis incidence by county in Vermont in 2018 (VT Dept. Health, 2018c)

Babesiosis

The third most common tick-borne illness in Vermont, babesiosis is caused by a microscopic parasite (*Babesia microti*) that is transmitted to humans by the blacklegged tick, the same tick that transmits Lyme disease and anaplasmosis (VTLyme.org, 2018). Babesiosis can also be transmitted, albeit less commonly, by blood transfusion or, even more rarely, from mother to unborn baby via congenital transmission (CDC, 2018). The disease, although less common than Lyme, has also drastically increased since 2005: only one case was reported in 2005, but twenty-one cases were reported in 2018 (Figure 8-27) (VT Dept. Health, 2018c).

Unlike Lyme, in which boys aged 5-14 and older men have the highest reported cases, most reported cases of *Babesiosis* in Vermont have been adults aged fifty-five years and older (VT Dept. Health, 2018c). Like Lyme and anaplasmosis, however, the cases have mostly been in the state's southernmost counties (Figure 8-28) (VT Dept. Health, 2018c).

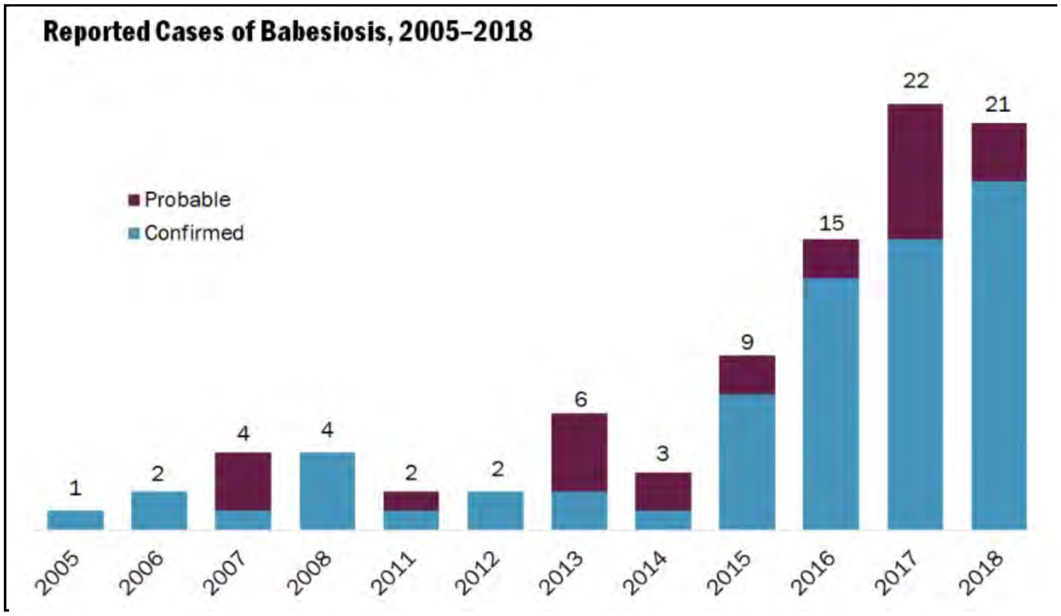


Figure 8-27: Reported cases of babesiosis in Vermont 2005–2018 (VT Dept. Health, 2018c)

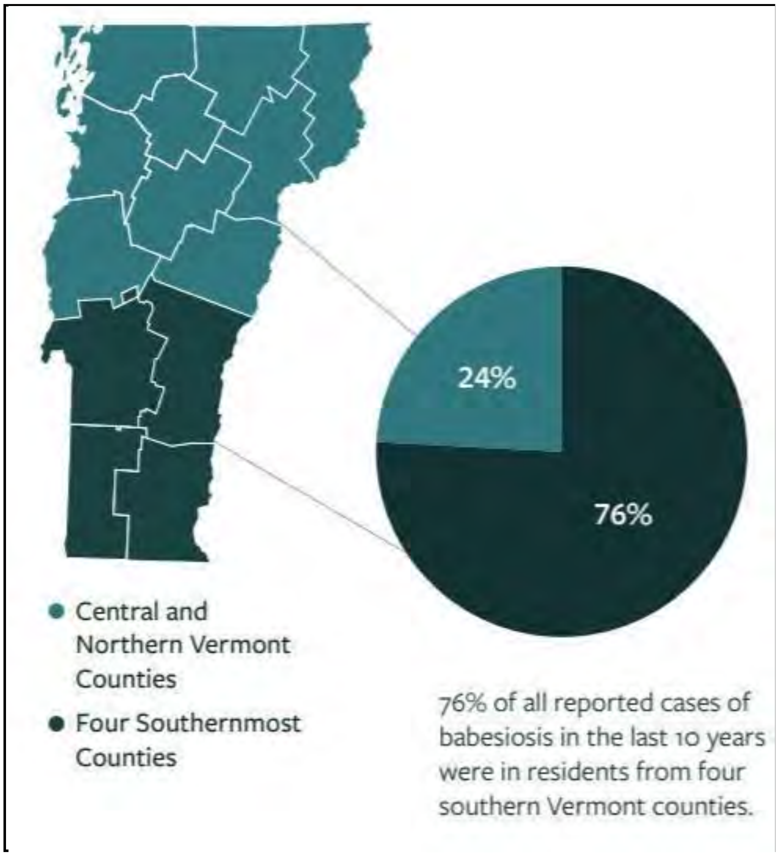


Figure 8-28: Reported cases of babesiosis in Vermont by county in 2018 (VT Dept. Health, 2018c)

Many people who are infected with the babesiosis parasite do not experience symptoms. However, if symptoms do present, often they include chills, fever, headache, sweats, body aches, loss of appetite, nausea, fatigue, and occasionally a type of anemia that leads to jaundice (CDC, 2018; VTLyme.org, 2018). Symptoms will generally present one to four weeks after the tick bite. Blood tests can diagnose babesiosis.

7.6.2 Mosquito-Borne Diseases

Mosquito-borne diseases are increasing in Vermont. While many Vermonters are familiar with the annoying sound of mosquitoes buzzing in the ears during summer and the itchy welts the bites cause, the idea of mosquitoes carrying disease is uncommon (Figure 8-29). However, two mosquito-borne diseases exist in Vermont: West Nile Virus (WNV) and Eastern Equine Encephalitis (EEE). Mosquitoes are inactive around 50℉ (10°C) and lower, become lethargic around 60℉ (16°C), and become much more active around 80℉ (27°C). Further, the time of development from egg to adult drops sharply from about 60 days at 59℉ (15°C) to 12 days at 68°F (20°C) and then declines further to about 6 days at 80–93℉ (27–34°C) (Rocklöv & Dubrow, 2020). With increasing temperatures, the transmission season in Vermont will lengthen, thus providing an environment for increased spread of WNV and EEE. These two illnesses are not prevalent in Vermont as of 2021. With climate change, Vermont is likely to see an increased risk of WNV and EEE as well as the potential of in-migration of mosquito species not previously in Vermont and with them the potential of different diseases (VT Dept. Health, 2018f).

Figure 8-29: A mosquito feasts. (Image: *https://www.cdc.gov/mosquitoes/index.html***)**

The United Nations International Panel on Climate Change (IPCC) declared mosquito-borne illnesses the most susceptible to climate change (K.R. Smith et al., 2014). Because mosquitoes are cold-blooded, they are largely sensitive to climate fluctuations (Ludwig et al., 2019; Patz, 2003). In addition, changes to climate impact mosquitoes' biting rates, survival, development, distribution, and range (Patz, 2003). Key climate changes that affect mosquitoes are increases in temperature and precipitation—both of which are expected to occur in Vermont (Ludwig et al., 2019). Especially significant are changes to precipitation: increased precipitation is linked to increased mosquito prevalence to a point, and then excess precipitation washes away larvae and eggs, while lack of precipitation creates stagnant pools where mosquitoes lay their eggs and live during early stages of development (Ludwig et al., 2019). Similarly complex, increases in temperature tend to decrease mosquito longevity but increase viral transmission rate, especially for EEE (Githeko et al., 2000).

West Nile Virus

WNV is an arbovirus that is rare in Vermont, with three reported cases or fewer per year from 1999–2019 (CDC, 2020a). With the first appearance of WNV in the United States in 1999 in New York City, the disease spread to other states, and even across the country by 2003 (Paz, 2015). Due to the dependence of the transmission cycle on climate conditions, changes in precipitation and increased temperatures in Vermont will encourage an increase in mosquitoes that carry WNV (Paz, 2015). Increased temperatures correlate with increased WNV replication rates, growth rate of vectors, viral transmission rate to birds, lower incubation time, and less amount of time between blood meals for mosquitoes (Paz, 2015). Increased precipitation has been found to lead to increased abundance of mosquitoes with WNV in the eastern US, and increased potential for disease outbreak in humans (Paz, 2015).

In Vermont, the Vector Surveillance Program monitors mosquito populations throughout the state and tests mosquitoes for WNV and EEE (Figure 8-30). In 2020, there were zero cases of WNV-infected mosquitoes (VT Agency of Agriculture, Food and Markets, 2020). However, in 2019, five mosquitoes had WNV (0.16% of total mosquitoes collected); in 2018, 157 mosquito pool samples were positive for WNV out of 2,997 pools (0.05%); and in 2017, 89 mosquito pools were positive for WNV out of 4,306 pools (0.02%) (VT Agency of Agriculture, Food and Markets, 2017, 2018, 2019a). These percentages are quite low, but with the changes expected in Vermont's climate, it is important to keep an eye on the changes in the amount of WNV, too. Since WNV has been found in 65 different mosquito species, the opportunity for geographical expansion, as well as increased rates in areas where it is already endemic such as in Vermont, is high. Not all mosquitoes have the same role in transmitting the virus: some species may contribute to early season amplification or serve as accessory bridge vectors in certain regions (Kilpatrick et al., 2005).

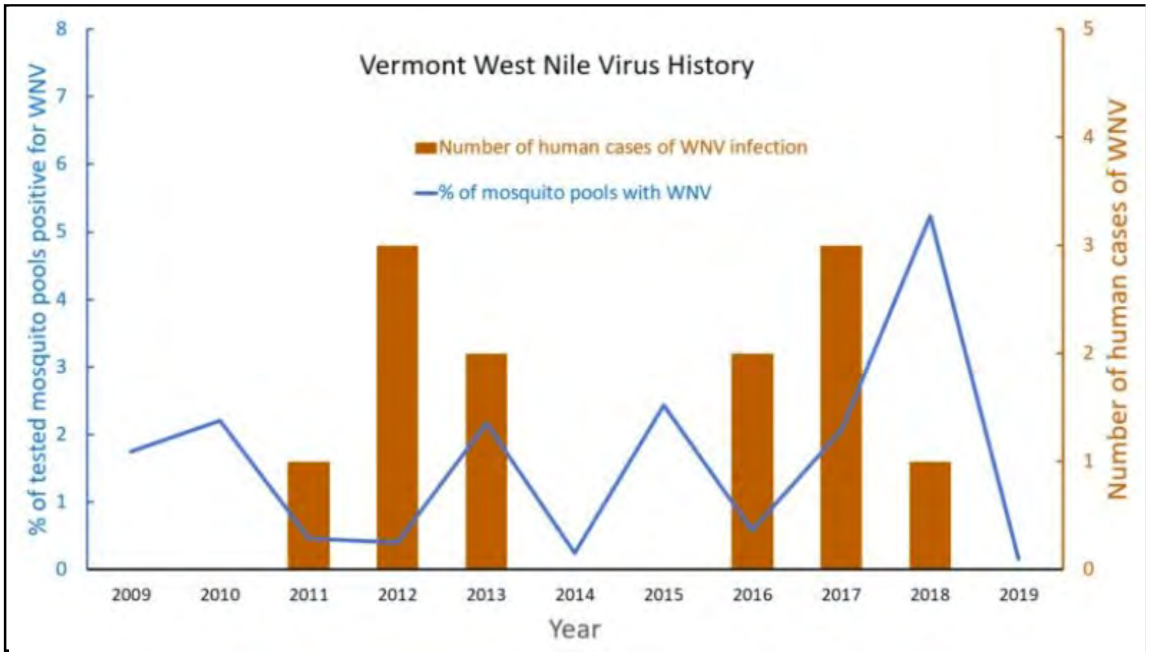


Figure 8-30: West Nile Virus history in Vermont 2009–2019, showing its cyclical nature (Fastie, 2019).

Symptoms of WNV include fever, headache, body aches, rash, and swollen lymph glands (VT Dept. Health, 2019d). Unfortunately, the virus has no cure, but symptoms can be treated. The disease is transmitted most frequently and commonly by mosquito bites (CDC, 2020a). However, it can also spread by blood transfusion and from mother to baby during delivery or via breastfeeding (CDC, 2020a). The occurrence of the disease is believed to be cyclical in nature, with low number years followed by two to four years of increased cases (Figure 8-30) (Fastie, 2019).

Eastern Equine Encephalitis

EEE is a rare neurological disease caused by a virus carried and transmitted by mosquitoes (CDC, 2020a). The incidence is rare in the United States, with nine confirmed cases in the country as of October 2020 (CDC, 2020c). The first outbreak of EEE in Vermont occurred on an emu farm in Rutland County in 2011 (Figure 8-31), although the virus had been detected in white-tailed deer and moose in 2010 (Saxton-Shaw et al., 2015; VT Agency of Agriculture, Food and Markets, 2019b). One year after the emu outbreak, the first human cases of EEE in Vermont were reported in Rutland County, with two individuals having been infected (Saxton-Shaw et al., 2015). Positive samples of EEE in mosquitoes occurred in 2011, 2012, 2013, 2014, and 2015, but no more human cases in Vermont have been reported since 2012 (VT Agency of Agriculture, Food and Markets, 2019b).

Figure 8-31: Emu. The first outbreak of EEE was found on an emu farm in Rutland County, Vermont (VT Agency of Agriculture, Food and Markets, 2013)

Like WNV, EEE is transmitted by mosquitoes, which are very susceptible to changes in climatic conditions. Mosquitoes testing positive for EEE have been found mostly in pools located in acidic, hardwood swamps in Rutland and Addison counties; thus, they have been designated areas for future risk of EEE virus (VT Agency of Agriculture, Food and Markets, 2019b). Because of EEE infections in horses in Franklin County in 2013 and positive mosquito pools in 2014 and 2015, Franklin County is also being monitored for future risk (Figure 8-32) (VT Agency of Agriculture, Food and Markets, 2019b). Vermont itself has not yet been hit hard by EEE, but Massachusetts has reported the most cases of EEE in the Northeast (CDC, 2020c).

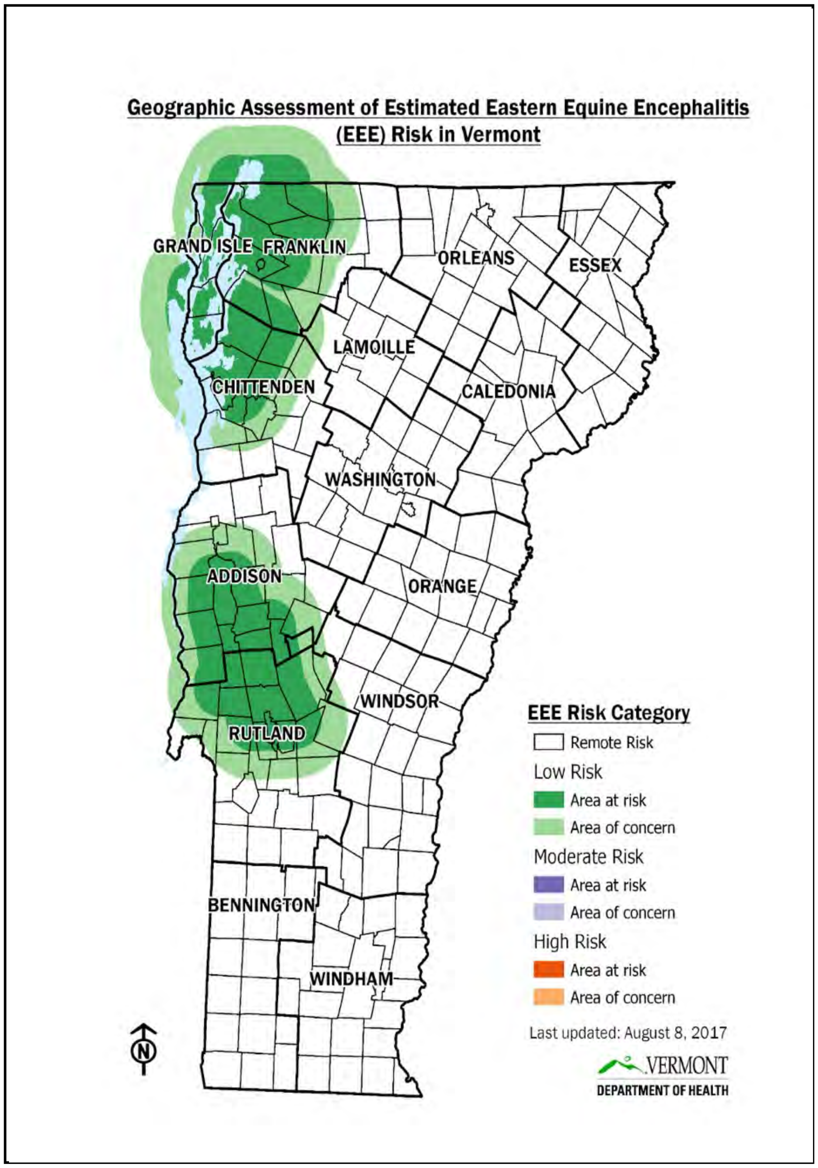


Figure 8-32: Risk areas for Eastern Equine Encephalitis (VT Dept. Health, 2019a)

The symptoms of EEE often occur 4–10 days after the initial infection and can include fever, chills, myalgia, arthralgia, and malaise (CDC, 2021c; VT Agency of Agriculture, Food and Markets, 2019b). More serious, neurological infection symptoms include nausea, vomiting, headaches, fever, seizures, diarrhea, drowsiness, behavioral changes, and coma (CDC, 2021c; VT Agency of Agriculture, Food and Markets, 2019b). This more serious version of the disease can have long-lasting neurological effects. There is no specific treatment for EEE in humans; current treatment focuses on reducing symptoms and fever. In addition, approximately one-third of all people infected with EEE die from the disease (CDC, 2021c; VT Agency of

Agriculture, Food and Markets, 2019b). People who engage in outdoor work and recreational activities in endemic areas are most vulnerable to contracting EEE. The individuals most vulnerable to developing EEE are individuals under the age of 15 and over the age of 50 (VT Dept. Health, 2019a).

Box 8.5: Eastern Equine Encephalitis (EEE)

In 2019, there were twenty cases and nine deaths of EEE in Massachusetts, Connecticut, and Rhode Island (Fastie, 2019). Despite this spike in cases in neighboring states, Vermont did not have a single case, nor were any positive mosquitoes identified in any of the 3,217 sites tested in the state. New Hampshire and New York also did not have any human cases, but EEE-positive mosquitoes were identified in both states (Fastie, 2019). While, like WNV, EEE is thought to be cyclical, it is unclear why Vermont avoided both human EEE cases and lack of EEE-positive mosquitoes.

7.6.3 Impact of Vector-Borne Diseases on Health

Increases in vector-borne illnesses in Vermont will burden the individuals affected and the health care system. As there has been an increase in emergency room visits from heat-related health issues, the increased incidence of vector-borne illnesses will likely put more strain on Vermont’s health-care system.

7.6.4 What You Can Do

This section explains how and what can be and is being done to address the changes in vector ecology in Vermont.

Ticks

The best way to prevent tick-borne diseases is to prevent tick bites. If you find a tick on your body, remove it quickly to reduce the risk of contracting Lyme disease. See a health care provider if you get sick or if you find a tick on you and are concerned about contracting Lyme. Lyme disease is treatable if caught early. Early diagnosis and treatment are important to avoid health problems related to Lyme disease (VT Dept. Health, 2019c).

Mosquitoes

The best way to prevent mosquito-borne illnesses is to prevent mosquito bites. Wearing long-sleeved garments and high socks and using sprays help prevent mosquito bites. In addition, avoid going outside during times when mosquitoes are most active: at dawn and dusk. Surveillance efforts in Vermont are informative about the prevalence of mosquitoes carrying diseases. The Vermont Department of Agriculture, Food, and Markets teamed up with other agencies in Vermont and tests thousands of mosquitoes every summer to understand trends of mosquito-borne illness prevalence in the state. The reports for each year since 2003 can be found on their website (https://agriculture.vermont.gov/public-health-agricultural-resource-management-division/plant-health-and-pest-management-2) (VT Agency of Agriculture, Food and Markets, 2021a).

Box 8.6: One Health

The One Health concept recognizes that the health of humans is connected to the health of animals and the environment. One Health has been used worldwide to address spillover of zoonotic diseases to humans, antibiotic-resistant bacteria, and more. The CDC uses a One Health approach by working with physicians, ecologists, veterinarians, and others to monitor and control public health threats and learn how diseases spread across animal, plant, vector, and human spheres (CDC, 2020b).

State vector-borne disease prevention is an excellent opportunity to put a One Health approach into action. Vermont's Department of Health and Agency of Agriculture are already involved with veterinarians, physicians, and ecologists to monitor and control Lyme, WNV, and EEE. This collaboration could be strengthened by including these actors when updating the next version of the Vermont Arbovirus Surveillance and Response Plan. Specifically, coordination with Department of Conservation ecological restoration projects could reduce mosquito habitat by accounting for farmers' roles in reducing habitat and early detection of diseases and could increase accounting for climate change effects in future planning.

7.7 WATER AND FOOD

With contributions from Michael Mezzacapo

In this section, the general trends in changes to water and food in Vermont, how that impacts human health, and what can be done to protect water and food in the context of climate change is discussed.

7.7.1 Changes to Water and Food

Measurable impacts from climate change already are altering the amount, timing, and quality of available water across the globe (Union of Concerned Scientists, 2010). Climate change and impacts to vital resources such as water are likely to negatively affect the four dimensions of food security—availability, access, utilization, and stability—and likely have a profound impact on human health (IPCC, 2019). Clean, adequate water access and healthy food supplies are essential to our well-being. Many view Vermont as a place with green pastures dotted with small farms nestled in rolling mountains and forest land for tree production and recreation (Figure 8-33). Working landscapes, including healthy farms and healthy forests, require proper stewardship and will need to be resilient in the face of a changing climate. Climate change will increase the negative impacts to both those that rely on natural resources for income and all citizens who choose to make Vermont their home.

Proper water supplies are needed to grow crops for animal production and feed growing human populations. Clean, sustainable water sources are not only needed for drinking, but also for irrigation and food preparation. Though Vermont exists in a humid climate, there are already impacts being felt from a changing climate. In 2018, during a severe drought around Franklin County, farmers had to haul water for livestock. USDA Environmental Quality Initiatives Program funding was made available for farmers to install new pipes and wells (Gribkoff, 2018). Though Vermont is getting wetter, climate change impacts the variability of dry and wet cycles.

Figure 8-33: The Winooski River in Montpelier, Vermont (Photo: Britannica, 2011)

Increased and sprawling residential and commercial development can place extreme pressures on wildlife, livestock, and crop production. More individual homes add to the number of onsite wastewater systems, which produce more nutrients and more chances to contaminate nearby water sources. Human health depends on a healthy environment. The state of Vermont is poised to face many challenges, as discussed in this Vermont Climate Assessment; however, basic survival and stability is predicated by access to clean water and the availability of healthy food. This section will briefly discuss how climate change can impact elements of water supplies, food production, and human health.

7.7.2 Water

Water distribution/quality

Climate change will continue to impact how precipitation is distributed around the state, though Vermont is getting wetter overall (see Climate Change in Vermont chapter). Extreme rainfall runoff causes soil erosion and flooding incidents, which impact water quality and can damage crops (USGS, 2021). Equally problematic are periods of extended drought, resulting in drinking water shortages and impacts to overall water quality in drinking and recreational waters (VT Dept. Health, 2017a). Drought periods followed by heavy rains can worsen pollution impacts because the soil is less absorbent, causing the rain to flow more easily off the surface (VT Dept. Health, 2017a). Stormwater runoff carries pollution such as fertilizers, toxins, sediment, animal wastes, wastewater, and other nutrient-rich materials quickly into rivers and lakes (VT DEC, 2018, 2021e). Human health is then compromised when these waters are used for recreation, drinking water, or irrigation of food crops.

Approximately 30% of the population in Vermont relies on a private drinking water source (VT Dept. Health, 2018b). These sources are not required to be tested regularly for contaminants, like nitrates. Both public and private drinking water wells can be subject to contamination from stormwater runoff (classified as nonpoint source pollution) (US EPA, 2015b). There is concern that excessive stormwater runoff from farms may be impacting nearby private drinking water wells. From 2007 to 2017, the Department of Agriculture tested 1,068 wells and found 63 private drinking water wells on or near farms that exceeded the state and federal drinking water standards for nitrate pollution, and 146 wells were at or over preventative action levels (Corwin, 2017).

Water-borne diseases/toxins

Many areas in Vermont have aging wastewater infrastructure and limited capital to invest in mitigation technologies, such as separated sewers, that can combat climate change impacts to these systems. Outdated wastewater systems can release sewage and stormwater into the environment after extreme rainfall events. Many drinking water sources in Vermont rely on surface water with these outfalls. The USGS estimates that in 2005, 440 million gallons of water were withdrawn every day in Vermont. Most withdrawals (88%) were from surface water sources, while the remaining (12%) were from groundwater sources (Medalie & Horn, 2010). As temperatures in Vermont increase, so will water temperatures. Warmer water temperatures will provide more favorable conditions for reproduction of waterborne pathogens and toxins (VT Dept. Health, 2017a). Several examples of impacts to human health are listed below.

E. coli is a specific type of bacteria that comes from fecal waste, including waste from humans, pets, livestock, birds, and wildlife (Lake Champlain Basin Program, 2021). Most types of *E. coli* are harmless, but certain strains can cause severe illness in humans, including diarrhea, stomach pain, nausea, and vomiting (Mayo Clinic, 2020). Exposure pathways include eating contaminated food, drinking untreated water, swimming near contaminated beaches, and contact with cattle or the feces of infected individuals (NY Dept. of Health, 2017). Because *E. coli* is ubiquitous in the environment, it can be difficult to understand future risks from *E. coli.* Recent research at the University of Guelph, Ontario, Canada concluded that climate change may trigger changes in bacteria to enable certain strains of *E.coli* to survive better in warmer soil and water conditions (van Elsas et al., 2011). As the climate warms in Vermont, environmental conditions could become more favorable for certain strains of *E. coli* to produce toxins and spread more easily, causing gastrointestinal illness and, in severe cases, death. In Vermont, E. coli presence in recreational water, such as Lake Champlain, is a common cause of beach closures. Closures typically occur after rainstorms flush sediment, bacteria, and pollutants into the lake (Figure 8-34) (Lake Champlain Basin Program, 2021). According to the Lake Champlain Basin Program, dog droppings are one of the leading causes of *E. coli* pollution. They offer suggestions on cleanup and how to keep dog feces from polluting the lake, including owners just picking it up where and when it happens.

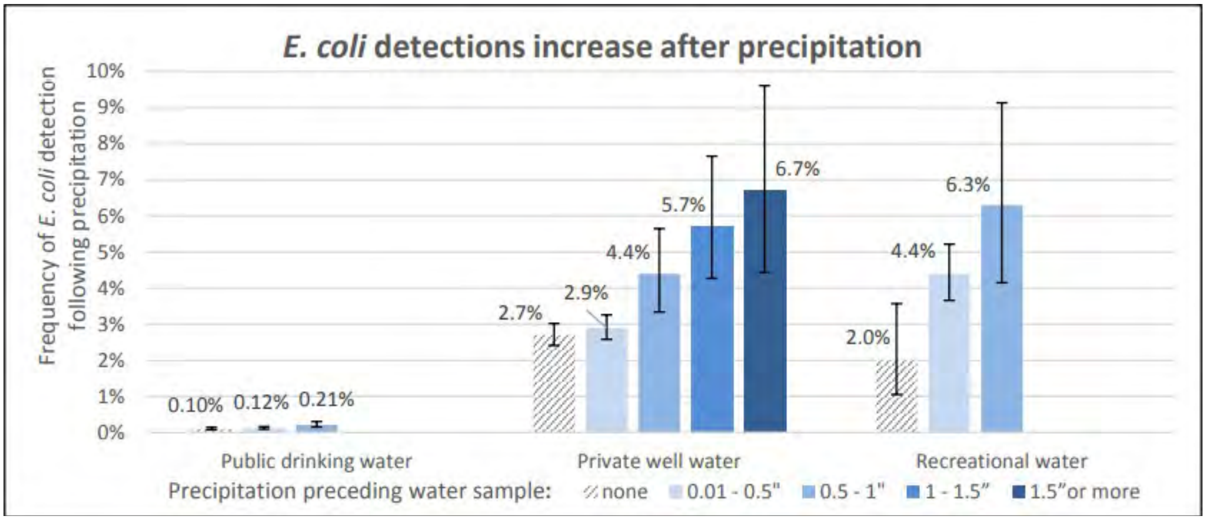


Figure 8-34: Percent of samples with E. coli detected in drinking water or E. coli above 235cfu/100 ml in recreational water following precipitation

Note: Few samples were available for public drinking water and recreational water for precipitation over 1 inch. These samples were combined with those from the 0.5–1-inch category (Vermont Department of Health, 2017)

Legionnaires' Disease: Legionella is a waterborne bacterium that can cause Legionnaires' Disease. Those infected may develop pneumonia or Pontiac fever (VT Dept. Health, 2020). Legionella grows best in temperatures between 77°F–108°F (25°C–42°C) in stagnant water (CDC, 2021a). Legionnaires' Disease spreads through aerosolization or aspiration of contaminated water in human-made building water systems (CDC, 2021a). Past outbreaks of Legionnaires' disease were reported in Vermont in 1977 and 1980, and research shows that risk of developing Legionella increases when weather is warm and humid (Simmering et al., 2017). Vulnerable populations include those over fifty years old, which comprises about one-sixth of Vermont's population.

Cyanobacteria blooms, also called algal blooms, are now a common sight on bodies of water in Vermont. Lake Champlain regularly experiences algal blooms, which often lead to beach closures and warnings about water quality. Cyanobacteria blooms occur when there are high levels of phosphorus and nitrogen in the water (VT Dept. Health, 2018e) This phosphorus and nitrogen tend to be higher after storms and heavy precipitation, when runoff from agricultural lands and other sources flows into the lake and deposits fertilizer. While most cyanobacteria are not harmful to human health, some carry toxins that can cause diarrhea, vomiting, rashes, sore throats, and runny noses. In addition, studies done on the particular toxins produced by cyanobacteria, called β-Methylamino-L-alanine (BMAAs), have shown a correlation between exposure to BMAA and neurodegenerative illnesses (Cox et al., 2018). The annual reports on cyanobacteria blooms make it challenging to assert whether these blooms are occurring more often (Figure 8-35) (Shambaugh, 2020). However, cyanobacteria are known to prefer warmer water temperatures, calm water, and nutrients like phosphorus and nitrogen (Lake Champlain Basin Program, 2018). Therefore, with warming temperatures in Vermont, and if nutrient runoff from farms and other sites continues, there could be an increase in blooms.

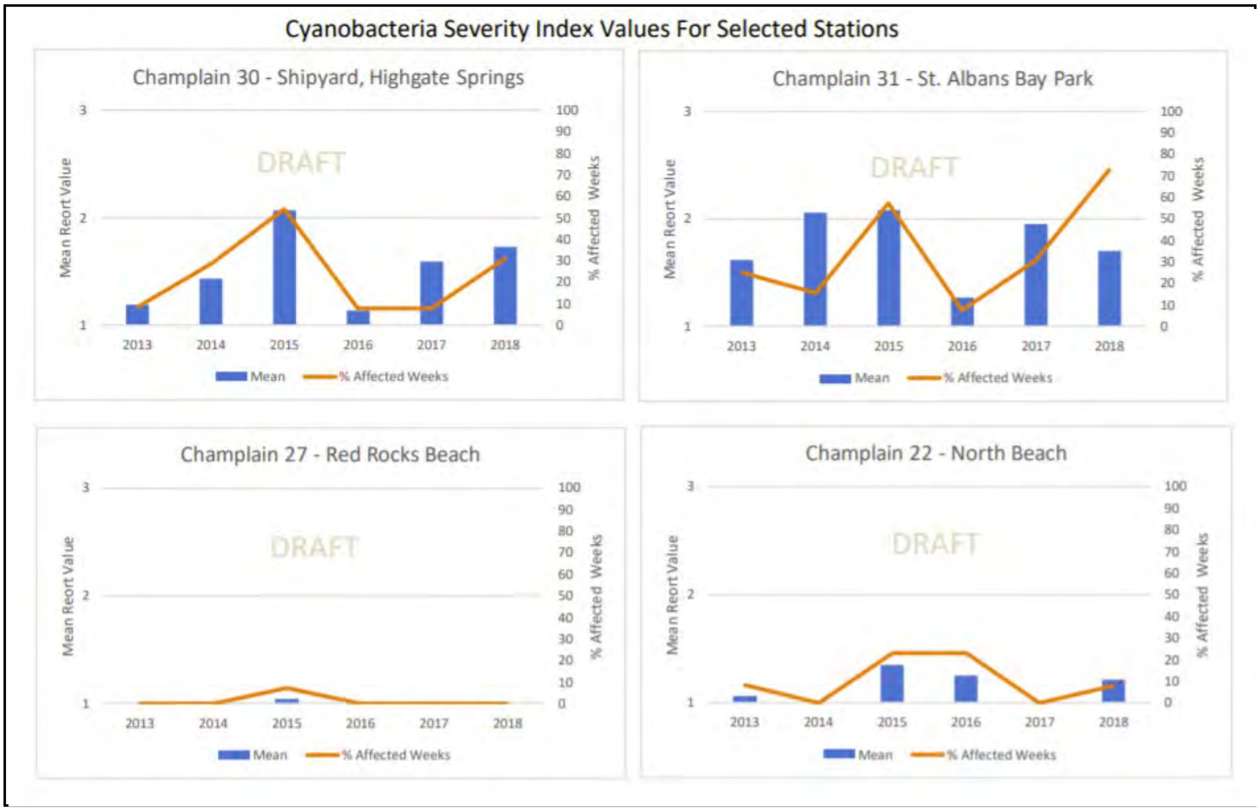


Figure 8-35: Cyanobacteria severity 2013–2018 in four areas of Lake Champlain that have strong long-term datasets (Shambaugh, 2020). The graphs are labeled "draft" because the cyanobacteria severity index is still in development.

Mercury is a potent neurotoxin and dangerous to human and ecosystem health (Tang et al., 2020). There are several types of mercury. However, elemental mercury can be converted to methylmercury in the methylation process through microbial activity in aquatic environments and easily be ingested and stored by aquatic plants, fish, and wildlife. Higher water temperatures from climate change can allow for more mercury methylation, which increases the amount of mercury in fish and animals that consume the fish, including humans (Stager & Thill, 2010). Fishing is widely practiced in the state. According to a 2020 Department of Fish and Wildlife annual angler survey, about 72,000 resident anglers fished for almost 1.8 million days. Fish are a healthy source of protein and Omega-3 fatty acids (American Heart Association, 2017). Increases in mercury levels may trigger more fish consumption advisories across the state and impact the health of vulnerable populations, including pregnant or nursing women and children. Many factors can impact mercury levels in the environment, including changes to fish communities and extreme climatic events. Further study is needed to identify future scenarios to better protect human health (Swinton & Nierzwicki-Bauer, 2020). More studies in Vermont are needed to evaluate wild fish consumption patterns among Indigenous communities, such as the Abenaki who have a long-standing tradition of hunting and fishing in Vermont, and recreational anglers to better evaluate total fish intake and human health risks from mercury.

Box 8.7: Mercury in Lake Champlain Fish

Recent research discovered mercury levels in Lake Champlain fish increased in the period 2011–2017, whereas levels previously had been steadily decreasing (Swinton & Nierzwicki-Bauer, 2020). Several reasons cause the increase in mercury, including "atmospheric deposition, lake temperature, chlorophyll-a, fishery dynamics, lake flooding and loading of total suspended solids" (Swinton & Nierzwicki-Bauer, 2020). Because of the toxicity of mercury and previous problems with pollution from atmospheric sources, the State of Vermont has monitored levels of mercury in fish tissue since 1987 and detected measurable concentrations in 95% of the samples collected from both lakes and rivers (VT DEC, 2021c, 2021d).

7.7.3 Food

Food production/security

A warmer climate can have variable impacts on crop production. According to the World Bank, a 3.6°F (2°C) increase in temperature puts around 100–400 million people at risk of hunger worldwide (Clayton et al., 2017; Friel & Marmot, 2011; McMichael, 2013). Equally important is the amount of land available for agriculture. Recently, Vermont has seen a decrease in available farmland. According to a 2018 report by the University of Vermont Extension and the Vermont Housing & Conservation Board, Vermont lost the equivalent of three Camel's Hump State Parks, roughly 64,000 acres total, in agricultural land between 1997 and 2012 (U. Vermont Extension & VT Housing & Conservation Board, 2018).

Aside from having favorable climatic conditions and available land to produce food, food production methods are important to food security and human health. Highly industrialized methods have cumulative effects on the environment, including contributing to climate change (Flesher, 2020). Future changes in Vermont's climate, such as warming temperatures or increased precipitation, along with production practices like wide-scale chemical fertilizer or pesticide applications may increase human exposure and cause diseases such as non-Hodgkin lymphoma and leukemias (Bassil et al., 2007). Farmers may use more pesticides to control agricultural nuisances because warmer temperatures can cause insect metabolism to rise and weeds to outcompete food crops (Deutsch et al., 2018). These chemicals often make it into the environment or our food supplies. One such pesticide widely used in Vermont is atrazine. Atrazine is a "restricted-use" pesticide used to control grassy weeds (Agency for Toxic Substances and Disease Registry, 2003). Because of its classification, it must be applied by licensed applicators and has restrictions on how close it can be applied near bodies of water. Studies have indicated that atrazine is a known endocrine-disruptor and can impact reproductive health (Sass & Colangelo, 2006). Atrazine is also highly mobile in the environment and can easily enter water, where it takes a long time to break down (Donley, 2019).

Box 8.8: Food Insecurity

In 2020, researchers at the University of Vermont conducted surveys to assess food insecurity. The results surprised researchers. Insecurity rose from 18.3% to 24.3% during the COVID-19 pandemic, or to nearly one in four Vermonters (Niles et al., 2021). This is nearly triple the levels of 2018. Respondents adopted coping strategies to address food access challenges, including buying foods that had a longer shelf life (77%), cheaper foods (66%), and even eating less (66%) (Niles et al., 2021). Food insecurity is compounded by other factors, including economic impacts or disease outbreaks, as witnessed in 2020-2021.

Climate change impacts can also disrupt food access by reducing production. Research shows that cold-weather crop production may be the most at risk from rising temperatures (US Global Change Research Program, 2010). Items such as field corn, wheat, and oats don't produce well when summer temperatures increase. This is even though the growing season may be six to eight weeks longer in 2067 (Ready-Campbell, 2017). Even warm weather crops like tomatoes and peppers can be severely impacted if temperatures exceed 90°F during certain parts of their life cycle (Dunnington, 2010; Frumhoff et al., 2008). Food insecurity has many negative associations with human health, including increased risks of some birth defects, anemia, lower nutrient intakes, cognitive problems, aggression, and anxiety (Gundersen & Ziliak, 2015).

The amount of food grown in Vermont may be reduced by climate change. For example, higher temperatures create small reductions in milk production in cows (Pragna et al., 2016). Even if citizens have adequate access to food, research has shown that nutritional values of the food can be impacted by rising CO_2 and temperatures (Myers et al., 2014; M. R. Smith & Myers, 2018). For instance, higher CO_2 concentrations lower the levels of protein and essential minerals of staple crops such as wheat, rice, and potatoes (Ziska et al., 2016). With lower levels of nutrients, people may be unable to meet their required intake of healthy food, and those who are already food insecure may be hit hardest. Lack of proper nutrition leads to many health issues, including diabetes, scurvy, anemia, general malnutrition, and developmental problems in children.

Food-borne Illness

Increased air temperatures provide more opportunity for dangerous pathogens to spread on crops and in food production. Additionally, warmer temperatures experienced in winter may also reduce the typical winter kill of pathogens (VT Dept. Health, 2017a).

7.7.4 Impact on health

As mentioned above, many other water quality-related health issues can arise including diarrhea, vomiting, liver damage, nerve damage, etc., depending on the issues in water. One example discussed in depth in this chapter is mercury. Mercury is a potent neurotoxin that can easily cross the blood-brain and placental barriers (VT DEC, 2021c). Impacts from mercury exposure include damage to the brain and kidneys, and impacts can be especially problematic in the fetus, children, and pregnant and nursing mothers (US EPA, 2015a). Mercury exposure can display severe, subtle, or no symptoms, depending on the form, amount, and length of exposure to the mercury consumed, and the current health of the individual (US EPA, 2015a). Exposed children may display differences in cognitive abilities, attention, language, fine motor skills, and visual spatial skills (US EPA, 2015a). Methylmercury poisoning (the most common type from consumption of fish) symptoms in adults may include (US EPA, 2015a):

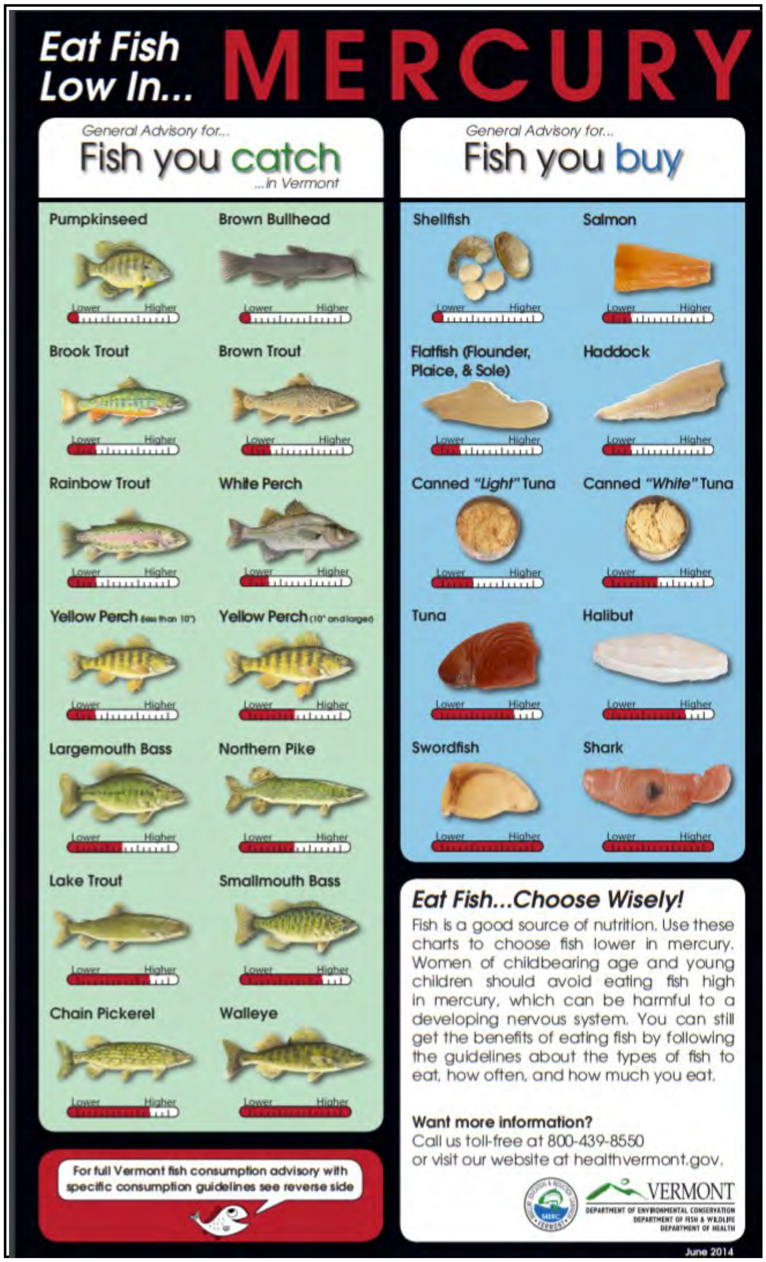
1. Loss of peripheral vision.
2. "Pins and needles" feelings, usually in the hands, feet, and around the mouth.
3. Lack of coordination of movements.
4. Impairment of speech, hearing, walking; and/or
5. Muscle weakness.

Other food- and waterborne illnesses in Vermont include salmonella, campylobacteriosis, cryptosporidiosis, hepatitis A, shigellosis, and norovirus. A full description of all these illnesses can be found on the Vermont Department of Health's Climate Change and Food and Waterborne Illnesses page (https://www.healthvermont.gov/health-environment/climate-health/water-foodborne-diseases) (VT Dept. Health, 2016d).

7.7.5 What You Can Do

The Lake Champlain Committee (LCC) involves citizen scientists to monitor and report cyanobacteria blooms. This information is then used to update weekly the Cyanobacteria Tracker Map, which is managed by the Vermont Departments of Health and of Environmental Conservation (VT DEC, 2021f). Volunteering with the LCC can increase your awareness of the activities being done to monitor water quality, fix lakeside infrastructure, and generally clean up Lake Champlain.

Keeping current on beach closings or water advisories can help prevent exposure to toxins and bacteria when levels are unsafe. In addition, anglers who enjoy eating the caught fish should follow the Vermont Department of Conservation's advice on mercury levels in fish, which can be helpful in determining your potential exposure to mercury (Figure 8-36).



Eat Fish...Choose Wisely!

Fish is a good source of nutrition. Use these charts to choose fish lower in mercury. Women of childbearing age and young children should avoid eating fish high in mercury, which can be harmful to a developing nervous system. You can still get the benefits of eating fish by following the guidelines about the types of fish to eat, how often, and how much you eat.

Want more information?
Call us toll-free at 800-439-8550
or visit our website at healthvermont.gov.

Figure 8-36: The levels of mercury found in various fish species in endemic fish in Vermont and store-bought fish (VT DEC, 2014)

Supporting local farms that practice regenerative or conservation tillage agriculture or that are transitioning to those agricultural practices can help to reduce the amount of fertilizer and runoff from those farms into water bodies. Following guidelines from the Vermont Low Impact Development Guide can help reduce the water quality impacts of new construction (VT DEC, 2010).

7.8 MENTAL HEALTH

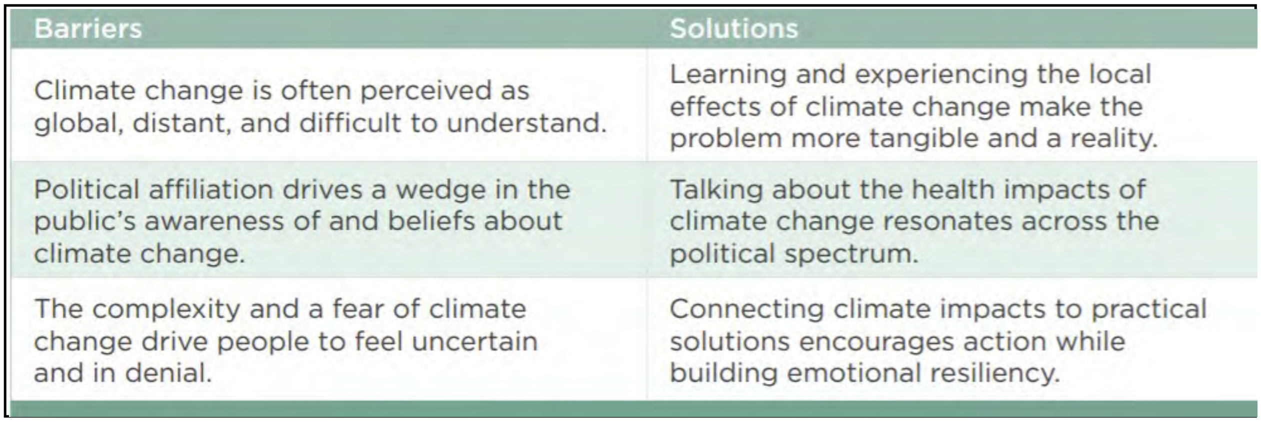
"Climate change is a human-caused problem, which is more difficult to cope with [mentally] than disasters that are beyond human control," says Thomas Doherty, PsyD, in a comprehensive report by the American Psychological Association, Climate for Health, and ecoAmerica on the impacts of climate change on mental health (Clayton et al., 2017). This report was written because most of the literature on climate change and health addresses the physical health impacts primarily and mental health impacts secondarily (Clayton et al., 2017). However, more and more there are clear links between changes to the climate and environment and mental health. This section outlines changes being observed in mental health, including climate-induced anxiety and suggests some ways to address these issues.

7.8.1 Changes in mental health

Well-being is intricately linked to the environment. Climate change has brought changes to mental well-being, both directly (e.g., through natural disasters like floods and storms) and indirectly (e.g., weakened and unstable infrastructure, rising sea levels, and forced migration) (Berry et al., 2010; Clayton et al., 2017; Schlanger, 2017). Impacts include increased anxiety, depression, shock, post-traumatic stress disorder (PTSD), compounded or chronic stress, and substance abuse (Figure 8-37). Other changes to mental health and behavior related to climate change include increased aggression and violence, increased senses of fatalism and hopelessness, and more mental health emergencies (Clayton et al., 2017; Schlanger, 2017). Luckily, the dialogue around climate change's impact on mental health has become more common in the past few years, which has led to new terms such as "eco-anxiety" to describe the fear, existential angst, and emotions surrounding climate change (Schlanger, 2017).

Figure 8-37: Interconnectedness of climatic changes on physical, mental, and community health, and vulnerabilities that can lead to the health issues (Clayton et al., 2017)

It can be difficult to grasp the connection between climate and health. Measures like maintaining a psychological distance, creating a political divide, and denial of the problem influence the way that people are able or unable to comprehend climate change. However, connecting climate change and personal health often increases the chances that individuals will take part in or support climate solutions, which, in turn, promotes psychological health (Figure 8-38) (Clayton et al., 2017). This is a center point of ecopsychology, a relatively new field that explores relationships between physical and mental health and the health of the environment. There are more and more studies that promote the interaction of people with their environment for physical and cognitive well-being (Robbins, 2020). Engaging with nature is “an antidote to stress: It can lower blood pressure and stress hormone levels, reduce nervous system arousal, enhance immune system function, increase self-esteem, reduce anxiety, and improve mood” (Robbins, 2020). Several organizations in Vermont use this idea of engaging with nature to promote healing and mental health through wilderness therapy, which is using extended time in nature combined with clinical therapeutics to promote well-being.



Barriers	Solutions
Climate change is often perceived as global, distant, and difficult to understand.	Learning and experiencing the local effects of climate change make the problem more tangible and a reality.
Political affiliation drives a wedge in the public's awareness of and beliefs about climate change.	Talking about the health impacts of climate change resonates across the political spectrum.
The complexity and a fear of climate change drive people to feel uncertain and in denial.	Connecting climate impacts to practical solutions encourages action while building emotional resiliency.

Figure 8-38: Barriers and solutions to comprehending climate change (Clayton et al., 2017)

Other, larger-scale changes can disrupt mental health, such as changes to businesses and hobbies due to storms and other disasters (VT Dept. Health, 2018a). Says Linda Silka, PhD, “New England is an example of vital infrastructure that is at risk from rising sea levels and of opportunities for psychologists to work with professionals in various fields to prepare for the effects” (Clayton et al., 2017). While Dr. Silka is speaking specifically of sea level rise, the sentiment of her statement can be applied to any impending disasters or climatic changes. Financial stress and changes to ways of life can be distressing and difficult to cope with, and we are likely to see these kinds of stresses arise with impending changes to Vermont’s climate. For instance, the ski industry provides economic benefit and a way of life for many Vermonters and other folks from out of state (see Recreation and Tourism chapter). With increasing winter temperatures, changes to snowpack could change the status quo for this industry and for those who derive enjoyment from it and could thus lead to increased personal and financial stress and anxiety.

With changes to vector ecology, air quality, and temperatures also come changes to physical health. Those affected by health issues like Lyme disease and asthma also tend to have increased burdens of depression or anxiety related to their condition (Asthma UK, 2020; Garakani & Mitton, 2015). With potential increases in both Lyme disease and asthma in Vermont, there may well also be a spike in mental health issues.

Box 8.9: Mental Health Access for Kids

The COVID-19 pandemic has thrown into relief the need for increased mental health infrastructure and access for children under the age of eighteen. Generally, there is an increase in demand for mental health care during the spring semester of the school year, and with social isolation and “skyrocketing anxiety” from the pandemic, demand for mental health care has grown even more. A decrease in available inpatient beds during the pandemic led to individuals waiting in emergency departments for hours. There is a seven-month waitlist to see a child psychiatrist at the University of Vermont Medical Center. If nothing else, the pandemic—like Tropical Storm Irene—has highlighted the need for improved mental health infrastructure and care, especially for children.

An experimental model called Pediatric Urgent Care for Kids has reduced the amount of youth ED visits by 33%. Launched in 2018 by United Counseling Service and Southwestern Medical Center in Bennington, this could be a model for the rest of the state to follow (Jickling, 2021).

Economically disadvantaged populations, those living with chronic diseases or pre-existing disabilities, and those living in unequal socioeconomic, geographic, and demographic locations tend to be particularly vulnerable to mental health issues (Clayton et al., 2017). Areas of increased vulnerability can be seen in the Vermont Department of Health’s Social Vulnerability Index map (Figure 8-39). It would be beneficial to update the data to see if/how the social vulnerability index has changed since 2015, but this tool is useful to predict potential areas where mental health resilience may be lower. Because lower socioeconomic status often positively correlates with increased mental health issues, understanding what parts of Vermont are particularly vulnerable in terms of economics, demographics, and more, can indicate where there might be more issues with mental health, and thus where the state can allocate its resources (Hudson, 2005; Reiss et al., 2019).

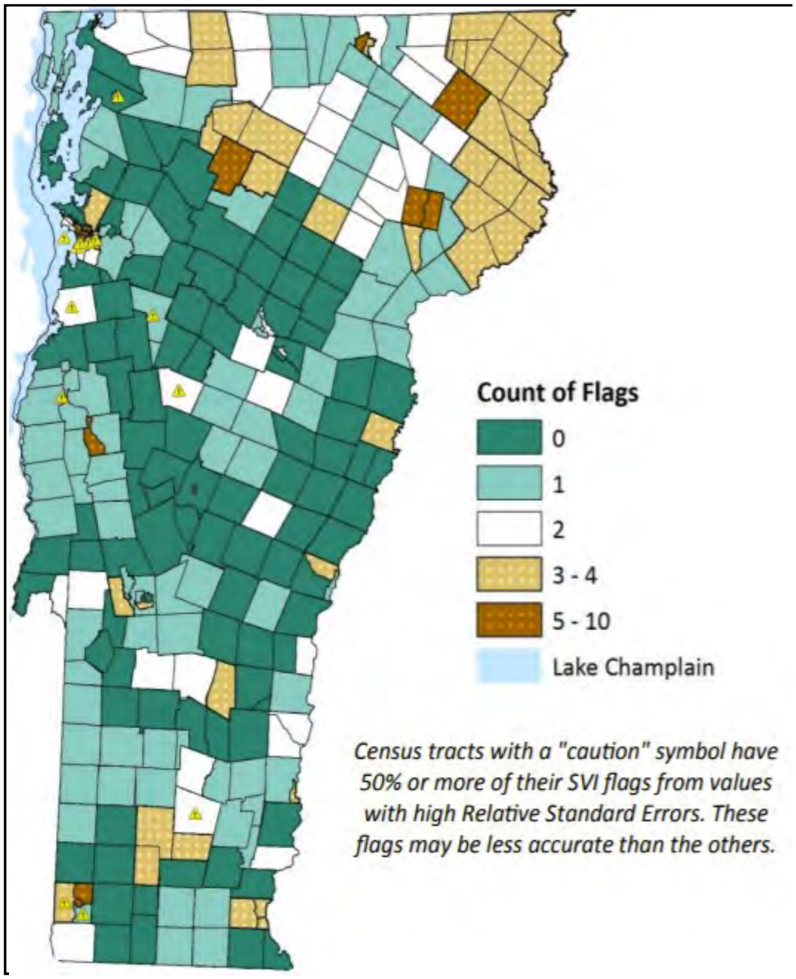


Figure 8-39: Social vulnerability index map of Vermont (VT Dept. Health, 2015)

Notes: Based on 2011–2015 data. The social vulnerability index has “16 different measures of vulnerability in three different themes: socioeconomic vulnerability, demographic vulnerability, and housing/transportation vulnerability. For each measure, [...] the most vulnerable 10% are assigned a flag. The overall vulnerability index is created by counting the total number of flags in each census tract” (VT Dept. Health, 2015).

As mentioned previously, Vermonters experienced long-term mental health impacts from Tropical Storm Irene. The storm necessitated the formation of short-term crisis intervention teams and a restructuring of the state’s mental health treatment facilities. A study conducted in Rochester, Vermont in 2014 found that 42% of the participants who reported negative emotions immediately after the storm also reported lasting negative emotions three years after the storm (Buschman et al., 2014). The individuals in the study that mentioned community involvement as part of their response and recovery from Irene tended to have a more positive emotional response and recovery to the storm (Buschman et al., 2014). This finding is a testament to the importance of community in mental health and resilience.

7.8.2 What You Can Do

Certain actions can improve mental well-being in the face of climate change. The previously mentioned comprehensive report on climate change and mental health makes several recommendations for individuals, communities, and mental health practitioners.

Individuals

Caring for the health of communities often starts with taking care of personal mental health and well-being: the overall well-being and resilience of communities depend on “the individuals within the community and how they react both as individuals and as a collective” (Clement, 2020). Four practical steps to improve individual resilience and mental health from the previously mentioned APA report include:

> *“1) Make and practice household emergency plans.*
> *2) Participate in mindset training to prepare for adversity and adaptation through increased awareness of our emotions.*
> *3) Care for oneself through healthy habits.*
> *4) Connect with family, friends, neighbors, and other groups to build strong social networks” (Clayton et al., 2017).*

Communities

Communities and community health play a vital role in promoting the mental health of the individuals within the community. Five ways communities can foster a positive environment for well-being are:

> *“1) Assess and expand community mental health infrastructure.*
> *2) Reduce disparities and pay attention to populations of concern.*
> *3) Engage and train community members on how to respond.*

4) Ensure distribution of resources and augment with external supplies.

5) Have clear and frequent climate–mental health communication" (Clayton et al., 2017).

Communities can also promote the use of public transport, which "invigorates community mental health" and increases community cohesion, promotes neighborhood walkability, and reduces depression and stress symptoms (Clayton et al., 2017). Promoting physical commuting (i.e., walking and biking) also decreases stress and depression symptoms (Clayton et al., 2017). In addition, the intentional use of green spaces promotes mental well-being, and clean energy can reduce health burdens by reducing the amount of particle pollution in the air (Clayton et al., 2017). By encouraging and implementing these strategies, communities can foster an environment to promote positive mental health and well-being.

Mental Health Professionals and Practitioners

The aforementioned report discusses ways for professional or mental health practitioners to support both communities and individuals. For communities, mental health professionals can:

"1) Become a mental health-related climate-literate professional.

2) Engage fellow public and mental health professionals.

3) Be vocal, model leaders within your communities.

4) Support national and international climate–mental health solutions" (Clayton et al., 2017).

Similarly, professionals can also help individuals to:

"1) Build belief in one's own resilience.

2) Foster optimism.

3) Cultivate active coping and self-regulation skills.

4) Maintain practices that help to provide a sense of meaning.

5) Promote connectedness to family, place, culture, and community" (Clayton et al., 2017)

There are many ways to foster a positive environment for promoting well-being and good mental health. While many of the above-mentioned recommendations are specific to climate-related mental health, they may also contribute to creating an inclusive and resilient community made up of engaged and resilient individuals. By working off this as a baseline, there is an increased ability for individuals and communities to have the tools and abilities to cope with climate change.

7.9 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

Confidence level	**Very high**	**High**	**Medium**	**Low**
Description	Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus	Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message 1: Climate change affects human health by exacerbating existing health problems and amplifying conditions for new health problems.	
Confidence level	Very high
Description	High consensus; multiple evidence bases; lots of documentation
References	VCA, 2014; IPCC, 2021; National Climate Assessment, 2018

Key message 2: Individuals who are children, over 65 years, of low socioeconomic status, Indigenous, or have previous health issues are more vulnerable to the health effects of climate change.	
Confidence level	Very High
Description	High consensus; multiple studies and evidence; lots of documentation
References	National Climate Assessment, 2018; IPCC 2021; Vermont Health Department

Key message 3: Warmer and more moist temperatures in Vermont are likely to create more habitat for disease-carrying ticks and mosquitoes.	
Confidence level	High
Description	Climate models have general consensus on warming trends; some studies done on vector and disease migration
References	Allen et al., 2019; Vermont Department of Health

Key message 4: Increases in the number and severity of natural disasters in Vermont will likely increase the risk of injury, illness, and death.	
Confidence level	Very High
Description	Much consensus on causal relationship between increased severity of storms and impact on health; lots of data
References	Fourth National Climate Assessment, 2018; Smith et al., 2014; FEMA.gov, 2021

Key message 5: Climate change could affect the quality and safety of food and water, which could lead to increases in food and water-borne illnesses.	
Confidence level	High
Description	High level of confidence in causal relationship between water and food changes and related illnesses
References	Union of Concerned Scientists, 2010; IPCC, 2019; State of Vermont, 2021

Key message 6: Decreases in air quality will exacerbate existing chronic diseases and decrease water quality.	
Confidence level	Very high
Description	High consensus on air quality and chronic lung diseases; multiple studies done
References	Dean & Green 2019; Smith et al., 2014; American Lung Association, 2020; Vermont Department of Health, 2019

Key message 7: Mental health is inextricably linked with environmental health. Impacts from climate change could contribute to mental health challenges.	
Confidence level	Very high
Description	High consensus on environment and mental health; multiple studies done; increasing documentation
References	Berry et al., 2010; Clayton et al., 2017; Schlanger, 2017; Robbins, 2020

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8 COMMUNITY DEVELOPMENT

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8.1 KEY MESSAGES

1. Flooding is the most likely natural disaster to occur in Vermont and should be accounted for in all community development and planning efforts in the state; however, extremes will become more common, so community development and planning efforts should also account for chronic hazards, such as drought.
2. Systems interconnections are essential to consider in community development and planning of future climate change scenarios, particularly in the context of disasters.
3. Vermont is expected to continue to have a favorable climate under future climate change projections, however, there is very little information to predict if the state will face an influx of climate migration.
4. Engaging in planning is essential for Vermont communities to access federal funding and to prepare for current and future climate change impacts, including population growth, flooding, and droughts.
5. Climate change will not impact all communities equally; the needs and capacity of vulnerable populations should be considered with all community planning efforts.

8.2 INTRODUCTION

Vermont encompasses 9,216.66 square miles (U.S. Census Bureau, 2010), has a population of 623,989 (U.S. Census Bureau, 2019), and is known for natural beauty and rural character. Vermont is composed of 251 cities, towns, and villages. Like in much of New England, local government occurs at the town level, not the county level, and many of the elected officials serve in a voluntary capacity (Paul & Milman, 2017). Over the years, the state has designed many efforts to combat development pressures, such as from an influx of second home buyers that threatened farmland and open space (DeWeese-Boyd, 2005).

This chapter applies a *resilience thinking* lens to community development (Table 9-1). At its core, community development can be thought of as the participatory processes and decision-making needed to make progress in a community. Or, as defined by Lotz (1971, p. 315), “community development is a general name to define the complex processes of socio-economic development and change.” Resilience thinking views communities as social-ecological systems (e.g., human communities are heavily interlinked with the natural environment) that, when faced with a disturbance (in this case, climate change and subsequent disasters), will either persist, adapt, or transform (Folke et al., 2010). Additionally, resilience thinking views social-ecological systems (i.e., communities) in terms of complexity theory, which emphasizes cross-scale interactions and integrated systems (Folke, 2006). By applying a resilience thinking lens to community development in the context of climate change, this chapter seeks to understand the likely ways climate change will cause disturbances in communities; to identify efforts the state of Vermont and its communities can undertake to persist, adapt, and/or transform; and to utilize community development strategies that form a holistic perspective to break down systemic silos.

Table 9-1: Resilience components and their application for community development and Vermont communities

Resilience component	What this means for community development	What this means for Vermont communities
Resilience of social-ecological systems (Folke et al., 2010)	Communities, in this case, are the social-ecological systems. Communities rely on and are influenced by the natural world; and in turn they also impact the surrounding environment.	This means that the interconnections between Vermont communities and the environment are important to consider in the context of resilience to climate change.
Resilience in the context of complex systems	Resilience theory and thinking is tied to complexity theory. Complexity theory describes systems defined by cross-scale interactions, emergent properties, and integrated systems (Folke, 2006).	For Vermont communities, implementing resilience thinking in the context of complex systems means that planning for resilience in the face of climate change should account for the connections between multiple systems (e.g., food, energy, water, the economy, environment, etc.) and should consider how the local scale connects to the regional and state scales, which connects to the national scale in terms of systems connections, decision-making, and other community actions.
Systems resilience principles: the 4 Rs - robustness, redundancy, resourcefulness, and rapidity (Cimellaro, Reinhorn, & Bruneau, 2010)	Systems resilience principles are often attributed to physical infrastructure systems, but they can be attributed to social, ecological, and economic systems as well. The four Rs refer to qualities of a system that can promote or enhance resilience. Robustness refers to strengthening a system so that it resists damage or disturbance. Redundancy means that there are backup systems or resources in case a disturbance breaks or destroys something that is relied on. Resourcefulness is often considered in terms of "capacity": does a community or system have the resources and capacity to respond to a disturbance? Rapidity means how quickly a response can be mobilized, for example, how quickly services can be restored following a disturbance.	In Vermont communities, these elements are essential to include in planning processes, especially those related to disasters and emergency management. Vermont communities rely on a number of infrastructure and other systems, so it is important to consider the "four Rs" in planning for these systems.

Resilience component	**What this means for community development**	**What this means for Vermont communities**
Resilience thinking vs. resilience as an outcome	While early academic work tended to consider “resilience” as an outcome-oriented concept, the field has come to view resilience as a process-oriented concept (Matyas & Pelling, 2015). In other words, resilience is more a way of thinking about a system and how to make decisions about it, as opposed to an outcome or a goal to be achieved. Resilience thinking is advocated, given the complex nature of human communities.	For Vermont, this means that resilience should not be thought of as a fixed outcome. Resilience should be thought of as a way of making decisions about community development. Resilience thinking allows communities, planners, and decision-makers to consider what resilience means within specific contexts and define the characteristics that would characterize improvement.
Social cohesion	Social cohesion, also called social capital or social infrastructure, refers to the bonds between individuals and social networks. In resilience research, social cohesion has shown to be an important factor in communities that fare better than others following disturbances (Townshend et al., 2015).	For Vermont, this means that the social ties between individuals and social networks should be accounted for when planning for or implementing resilience-building projects.
Diversity, equity, inclusion, and justice (DEIJ)	Climate change will not impact all areas and all populations equally.	For Vermont, this means that DEIJ should be accounted for in all planning and resilience-building efforts. This could mean purposely analyzing data by demographic or spatial group instead of in aggregate, considering how resources and services can be distributed equitably, and ensuring that community members (especially from populations that may face inequitable impacts) are included in the planning, development, or policy process.

Communities rely on a number of infrastructure systems, also called critical infrastructure systems or lifeline systems, for their health and well-being. Infrastructure systems include food, energy, water, communications, transportation, and healthcare. Within a community, lifeline systems are heavily linked with one another, so damage to one system can cause subsequent damage to the other systems. These infrastructure systems exist in economic and social systems (including governmental, legal, and cultural systems). Climate change will have effects on these systems (think loss of ski tourism and maple sugaring, alone) that will reverberate into each other.

This chapter will explore how climate change is already, or likely to, impact Vermont communities and the interconnected systems upon which they rely. The other chapters within this Vermont Climate Assessment provide in-depth coverage of the impact climate change will have on individual systems and sectors. This chapter builds from the material covered in the other chapters, so the reader is encouraged to peruse those chapters for more information on individual systems.

This chapter will first detail the climate change impacts that are most relevant to Vermont in the context of community development and present some adaptation and mitigation strategies for each. Next is a discussion of how climate change is likely to impact the “lifeline” systems that Vermont communities rely on so that community or regional planners can take into consideration these systems interconnections when making development decisions. Finally, this chapter details community- and state-level planning efforts in progress and provides examples of other efforts being undertaken in various cities in the United States that Vermont could consider.

8.3 CLIMATE CHANGE IMPACTS RELEVANT TO COMMUNITY DEVELOPMENT

Key steps to increase resilience, especially resilience as applied to community planning, are to identify likely future scenarios and threats and then ensure that there is a plan in place to both mitigate the effects of those scenarios and recover from events quickly. In that vein, this section will summarize a few likely threats that Vermont should account for in planning efforts: disaster declarations, flood events, droughts, and potential impacts from climate migration. This is not an exhaustive list.

8.3.1 Disaster Declarations

Disasters in Vermont previously declared by the Federal Emergency Management Agency (FEMA) indicate which kinds of hazards Vermont should account for in community development decisions and planning efforts (Table 9-2).

Table 9-2: FEMA disaster declarations in Vermont (FEMA, n.d.) as of October 2021, in order by type and most recent date. Rows shaded grey indicate that the disaster declaration included flooding.

Type of Declaration	#	Date(s) of Declaration
COVID-19 Pandemic	2	March 13, 2020; April 8, 2020
Tropical Storm Henri	1	August 22, 2021
Severe Storms and Flooding	27	September 29, 2021; January 17, 2020; June 14, 2019; July 30, 2018; January 2, 2018; August 16, 2017; July 29, 2015; June 11, 2014; August 2, 2013; June 13, 2013; November 8, 2011; July 8, 2011; June 15, 2011; September 12, 2008; July 15, 2008; August 3, 2007; May 4, 2007; September 23, 2004; September 12, 2003; July 12, 2002; January 18, 2001; July 27, 2000; June 30, 1998; July 25, 1990; September 11, 1989; June 18, 1984; August 30, 1969
Severe Winter Storm	3	February 3, 2015; January 29, 2014; January 14, 2009
Severe Storm, Tornado, and Flooding	2	June 22, 2012; August 15, 2008
Tropical Storm Irene	2	September 1, 2011; August 29, 2011
Severe Storm	1	December 22, 2010
Snow	1	April 10, 2001
Tropical Storm Floyd	1	November 10, 1999
Severe Ice Storms, Rain, High Winds and Flooding	2	January 15, 1998; August 5, 1976
Excessive Rainfall, High Winds, and Flooding	1	July 25, 1997
Extreme Rainfall and Flooding	2	June 27, 1996; August 16, 1995
Ice Jams and Flooding	2	February 13, 1996; March 18, 1992
Heavy Rain, Snowmelt, and Flooding	1	May 12, 1993
Drought	1	September 6, 1977
Severe Storms, Flooding, and Landslides	1	July 6, 1973
Flooding	1	March 17, 1964
Drought and Impending Freeze	1	November 27, 1963

As shown in Table 9-2, forty-two of the fifty-two FEMA disaster declarations since 1963 have included flooding. Nine of the fifty declarations have been related to winter storms, snow, or ice storms and two of the fifty were for drought. Based on this history, it is clear that people involved in community development, especially planners, should include severe storms and flooding in all future scenarios and planning efforts. More prolonged dry spells and drought are expected in coming decades, so they should also be considered in planning and community development (see the Climate Change in Vermont chapter and Water Resources chapter).

8.3.2 Flooding

As exemplified by Tropical Storm Irene and the majority of disaster declarations since 1963, Vermont has a history of flooding, and climate change is projected to increase the frequency and severity of flood events in the state. The Water Resources chapter and Climate Change in Vermont chapter discuss the causes and impacts of flooding across the state of Vermont. This section will focus on flooding in the context of human communities: what has been done and can be done to reduce the impacts of flooding on Vermonters and their communities.

8.3.2.1 Flood Mitigation Strategies

Since Vermont has already experienced flooding and is projected to face increased threats of flooding in the future, this section describes some strategies to build resilience to flooding. The “International Lake Champlain-Richelieu River Study Board” is conducting a study to better understand the “the causes, impacts, risks and potential solutions to flooding in the basin” (International Joint Commission, 2020). A summary report (International Lake Champlain-Richelieu River Study Board, n.d.) and full report (International Lake Champlain-Richelieu River Study Board, 2019) are available. The report cites natural geographical and meteorological factors that affect flooding (e.g., physical geography, changes in weather patterns, the baseline lake level, and vegetation within the Richelieu River), but it also cites anthropogenic changes. These anthropogenic changes include population growth and land use changes (such as development in the floodplain, wetlands loss, and impervious surfaces), channel alterations and instream construction, and flood storage reservoirs (International Lake Champlain-Richelieu River Study Board, 2019). These anthropogenic factors mean that community development and planning decisions can affect future flood impacts, and therefore development decisions should be carefully considered.

A key flood mitigation resource in the state and to environmental justice, Flood Ready Vermont (State of Vermont, 2021g) is a resource to support community planning. It provides information on flood impacts to the state, strategies to mitigate flood risk and impacts, and planning resources. Importantly, it notes that flood impacts are not shared equally among Vermont residents. For example, Tropical Storm Irene and the spring flooding of 2011 destroyed 154 mobile homes in parks in Vermont, and 12% of mobile home parks in the state are located in floodplains (Baker et al., 2014).

Flood mitigation resources and strategies are described below.

- **Community Rating System**: Currently, seven Vermont communities are receiving discounts on their National Flood Insurance Program (NFIP) premiums through their communities' participation in the Community Rating System (CRS) (FEMA, 2019). CRS is a program through which communities receive increasing discounts in flood insurance premiums by demonstrating how they have undertaken certain flood risk reduction actions. These actions range from education and outreach through posting information at risk areas to participating in buyout programs to remove properties from the floodplain. As this program can be complicated, a Community Rating System Green Guide was released in 2017 to aid communities in undertaking some of the more environmentally friendly actions (Association of State Floodplain Managers, 2021).
- **Emergency Relief and Assistance Fund (ERAF)**: ERAF provides state funding as a match for federal funding received after federally declared disasters (State of Vermont, 2021c). Through ERAF, the state will pay additional amounts if the damage occurs when a community has taken certain protective or preventative actions. The Lake Champlain Sea Grant has summarized these actions through Watershed Scorecards, such as for the Lamoille, Missisquoi, and Winooski Watersheds (Lake Champlain Sea

Grant, 2021). Additionally, participation in the Community Rating System can help communities qualify for ERAF.

- **Buy-outs and Encroachment Removal:** Buyouts and encroachment removal refer to when the state or federal government purchase properties in a floodplain (often repetitive loss properties) and remove the structures from the floodplain. Buyouts and open space preservation are actions specified to increase a community's rating within the Community Rating System. In Vermont, buying out homes in vulnerable areas as a flood mitigation strategy began after the flooding from Tropical Storm Irene (Davis, 2017). Vermont is pursuing the buyout of 130 residences with funding through the FEMA Hazard Mitigation Grant Program with a Housing and Urban Development Community Development Block Grant match portion (State of Vermont, 2021f).

- **Flood-proofing and Elevating:** Another flood mitigation strategy is to flood-proof and elevate structures, such as through elevating the bottom floor of the structure, elevating utilities (e.g., electricity), switching from a basement to an above-grade crawl space, and providing vents so that flood water can enter and exit a space freely (State of Vermont, 2021b).

- **Floodplain, Wetland, and River Corridor Restoration:** A key flood mitigation strategy is to preserve and restore floodplains and river corridors. These ecosystems can buffer communities from negative flood and other climate change impacts. A study of the Otter Creek wetlands and floodplains in Middlebury, Vermont estimated that upstream flood mitigation by wetlands and floodplains would provide damage reductions of 84–95% during Tropical Storm Irene and 54–78% in reductions averaged across ten other flood events (Watson et al., 2016). In a study of the Lake Champlain-Richelieu River Watershed, wetlands were shown to be an important part of the watershed, and the study recommended they be maintained as storage areas in the upper parts of the watershed (Rousseau, 2020).

- **Planning and Funding**: Vermont and Vermont communities are engaging in many planning efforts and have leveraged federal funding sources. These will be described below in the section "Vermont Planning in the Face of Climate Change."

8.3.2.2 Stormwater Management via Green Stormwater Infrastructure

Another flood mitigation strategy is to improve the stormwater management system. Stormwater management refers to the systems that deal with water from rainfall, flooding, and other water-related events to reduce potential damages from increased water levels. Green infrastructure (GI) is a type of stormwater management and flood mitigation strategy that involves the use of environmentally friendly or natural materials (e.g., green roofs, rain gardens, bioswales). GI has been used in Vermont's urban areas long before state and United States Environmental Protection Agency (EPA) stormwater standards were made available. In Vermont, the 2017 Vermont Stormwater Management Manual Rule and Design Guidance added green infrastructure strategies into the design requirements for certain projects (Vermont Agency of Natural Resources, 2017) and the state supports a GI manual for homeowners (Vermont DEC, 2018b). The Green Infrastructure Collaborative is a partnership between the Lake Champlain Sea Grant and the Vermont Department of Environmental Conservation that promotes GI practices in Vermont. The state strongly supports GI, as evidenced by this explanation: "Humans rely on GI for a variety of ecological goods and services, such as clean water and air, carbon sequestration, flood control, and climate change mitigation. GI can also increase property values, enhance tourism and recreational opportunities, create jobs, and improve human health and well-being" (State of Vermont, 2021d). Nature-based solutions for stormwater management also utilize wetlands and forests to retain water during extreme water highs and lows. Groups like The Nature Conservancy Vermont protect land and thus provide these nature-based solutions. Other groups working on nature-based solutions for water management (e.g., riparian tree planting) include the new Watershed Forestry Program with Lake Champlain Sea Grant, the Natural Resource Conservation Service, the Intervale, multiple local watershed groups, and American Forests.

Several United States cities have resilience plans that deploy green infrastructure. These plans can serve as examples for Vermont communities seeking to integrate GI into their flood mitigation and stormwater management strategies. Following are strategies communities have used to increase GI.

- **Integration into Street/transportation Projects**: Recognizing the ability of GI to create multiple benefits, especially as compared to traditional stormwater management techniques, some cities are targeting GI implementation in conjunction with street improvement projects (e.g., City of Berkeley, 2016, p. 34).

- **Demonstration Projects**: Demonstration projects can raise public awareness and garner public support for GI implementation (e.g., City of New Orleans, 2015, p. 39).

- **Green Infrastructure and Stormwater Management Plans**: Several United States cities have developed plans dedicated to implementing GI and stormwater management (e.g., Oakland, CA has both a GI plan and a stormwater management plan) (City of Oakland, 2016).

- **Dedicated Funding to Green Infrastructure**: Cities have dedicated funding sources for the implementation of GI projects (e.g., Honolulu, HI has a stormwater enterprise fund) (City and County of Honolulu, 2019).

- **Education and Outreach**: Lake Champlain Sea Grant has a stormwater management curriculum (GI focus) for middle and high school students and builds capacity for teachers to teach the topic (accessible online at go.uvm.edu/stormwatered) (Stepenuck & Eaton, 2020).

- **GI Certification Programs**: There is a national GI certification program that could be adopted in Vermont (EnviroCert International, Inc., 2021). Lake Champlain Sea Grant is considering a state certification program that would include GI maintenance, such as has been done in New Hampshire at the Stormwater Center (University of New Hampshire, 2021).

It is worth noting that many GI projects or programs are suited to municipal activities. While some GI projects can be implemented by businesses or residences (e.g., green roofs, rain gardens), the materials or installation may be cost-prohibitive (e.g., renting a backhoe for rain garden development) and therefore more limited in scope without wider programming or support.

8.3.3 Drought

While drought was only declared as a FEMA disaster twice in the past fifty-five years, Vermont will experience greater variability in water-related extremes: an increase in overall precipitation yet more frequent dry-spells and drought. More information on how climate change may increase droughts in Vermont is found in the Extreme Events section of the Climate Change in Vermont chapter. In the context of community development, it is important to consider the variability in precipitation that the state will experience. The state is projected to have an overall increase in the amount of annual precipitation and experience periods of drought. This variable presents planning challenges for communities.

Droughts can impact Vermont communities in terms of agricultural production, water supply, impacts to forestry and wildlife, and ultimately, human health. As stated in the Water Stress section of the Agriculture and Food Systems chapter, drought conditions in Vermont will become more variable and directly impact growing seasons. For example, the state experienced droughts for much of the 2016, 2018, and 2020 growing seasons, and as of May 2021, 75% of the state is in moderate drought (NOAA & National Integrated Drought Information System, n.d.). In 2020, farmers reported at least $27 million in crop losses from the drought (McCallum & Picard, 2020).

Three out of ten Vermont households get their drinking water from private wells (Vermont Department of Health, 2021a), and about 60% of Vermonters rely on groundwater for drinking (VT DEC, 2018b). Drought can limit these households' access to water supply. Towns with already limited water supply will be further stressed by drought conditions. Efficient water use and water systems are increasingly necessary (see the Water Resources chapter). For example, the company Fresh Water Haulers in Underhill has seen an increase in the number of dry wells they have been asked to replenish. They reported, “I’ve seen this going on for about six years now. Every year it gets a little drier” (McCallum & Picard, 2020).

On a brighter note, the stormwater management strategies listed above may be able to decrease flooding and increase access to water during times of drought (McCallum & Picard, 2020). For more information, see the Water Supply section of the Water Resources chapter.

8.3.4 Climate Migration

Climate change is a slow and steady process punctuated by severe events. Consequently, people may decide to move to more favorable locations either slowly as long-term decisions or quickly and in larger pulses in response to disasters. In Vermont, there are two kinds of impacts of climate-induced changes and migration. The first are the direct results of climate change – for example increased flooding or droughts that may leave certain parts of the state less habitable than previously and lead to migration to other areas. The second are the more indirect effects of a changing climate and potential in-migration from other regions both nationally and internationally. Thus, while Vermont itself may not be exposed to certain risks, other communities that find themselves vulnerable to climate change impacts like extreme heat (Winkler & Rouleau, 2020) and coastal sea level rise (Hauer, 2017) may look for safer options. Some scholars have speculated that populations in at-risk regions may consider migrating to safer, less vulnerable areas (Hauer, 2017). Some climate projection maps indicate that Vermont may remain a “favorable” location under future conditions (Shaw et al., 2020). An example of climate migration is a family who “moved to Vermont last year from Richmond, Va., where they had a small farm with chickens and rabbits. [...] they had considered installing solar panels on their property and going off the grid, but southern Virginia’s increasingly hot summers, combined with the bleak ecological prognosis, compelled them to go north instead. [...] ‘We figured that people are going to be on the move in the decades to come, so we wanted to move to a state that had already done some work as far as renewables are concerned,’ [the family] said” (Edgar, 2021).

Such speculation has led to questions for policymakers, government officials, and local communities about how and whether to plan for an influx of *climate migrants*. There is currently no data to suggest that any such in-migration is on the immediate horizon. Indeed, while Vermont has a long history of both labor migration and a robust refugee resettlement program, both are relatively small in scale and concentrated in the northern parts of the state. In fact, for well over a century, Vermont has grappled with an *out-migration* dynamic, especially of youth, that state leaders have attempted to address (Bolduc & Kessel, 2015). The main population growth centers in Vermont are primarily in Chittenden County and the metropolitan area surrounding its main city of Burlington; it is here that the majority of both international and national migrants to Vermont settle. Issues of transportation access, housing and employment availability, and a lack of diversity in rural areas have contributed to these spatial settlement patterns (Bose, 2014). Studies of resettled refugees, mainly from Bhutan, Bosnia, Burma, Congo, Iraq, Somalia, Sudan, and Vietnam, within Chittenden County (where nearly all have been placed) suggest that integration has been largely a success, with strong levels of employment, home ownership, entrepreneurship, and educational outcomes (Bose, 2020).

Climate migration brings into question the agency of those moving to new locations; climate migration can occur voluntarily and involuntarily. For example, Tacy, Hanson, and Poulin (2020) conducted an assessment of climate migration in Vermont and concluded that the largest group of people migrating to Vermont will likely be voluntary “amenity migrants” (e.g., white, wealthy, and making an intentional decision to move to the state). The next most common groups likely to move to Vermont are those in search of work due to collapsed industries and disaster migrants (i.e., those fleeing a disaster in another region) (Tacy, Hanson, & Poulin, 2020). If climate migrants do come to Vermont, they are likely to settle in Chittenden County and smaller towns with “amenity value” (Tacy, Hanson, & Poulin, 2020), continuing trends seen during the in-migration patterns during the COVID-19 pandemic. Involuntary climate migrants may be fleeing a disaster that destroyed homes and have no choice other than to move. Involuntary migrants also may include refugees who may have had no choice but to settle in Vermont. Considering the agency of migrants brings into question: just because amenity migrants are most likely to move to Vermont, is this equitable? Should the state consider programming and services to ensure that those most impacted by climate change and climate change-induced disasters (both in-state and out of state) have the same opportunity to move to more favorable climatic conditions?

One thing is clear when it comes to how climate migration will impact Vermont: there is a lot of uncertainty, many questions remain, and there are many important avenues for future research. Questions remain as to what kind of infrastructure and planning is needed to provide appropriate support to potential climate migrants. for example, what kinds of support in terms of housing and employment should be considered for migrants from other parts of the United States? For international migrants, what language or cultural support might be available? What kinds of capacities—numbers of in-migrants and available resources—should local communities plan for? What kinds of community planning strategies (e.g., low-impact development, smart growth strategies, changes to zoning and land use regulations) should be in place to prevent amenity migrants from buying undeveloped land that could otherwise serve flood mitigation or carbon sequestration services? Future research could investigate trends in home sales following hurricanes, wildfires, or other climate change-related disasters to better understand what kinds of migration pulses could be expected due to extreme events.

8.3.4.1 Migration Associated with COVID-19

Migration due to the COVID-19 pandemic could shed light on the potential impacts of climate-induced migration. The pandemic spurred “urban flight,” in which residents of urban areas moved to more suburban or rural areas with lower population densities and (perceived or actual) lower rates of COVID-19 transmission. Vermont saw a 38% increase in residential property sales to out-of-state buyers in 2020 (Figure 9-1), with over 1,000 more property sales in 2020 than in 2019 (VCGI, 2021). Stowe had the highest number of out-of-state residential property buyers in 2020, with $132,100,000 in sales (VCGI, 2021). Overall, sales were greatest in southern Vermont, the Mad River Valley, and Lamoille and Chittenden counties (Petenko, 2021).

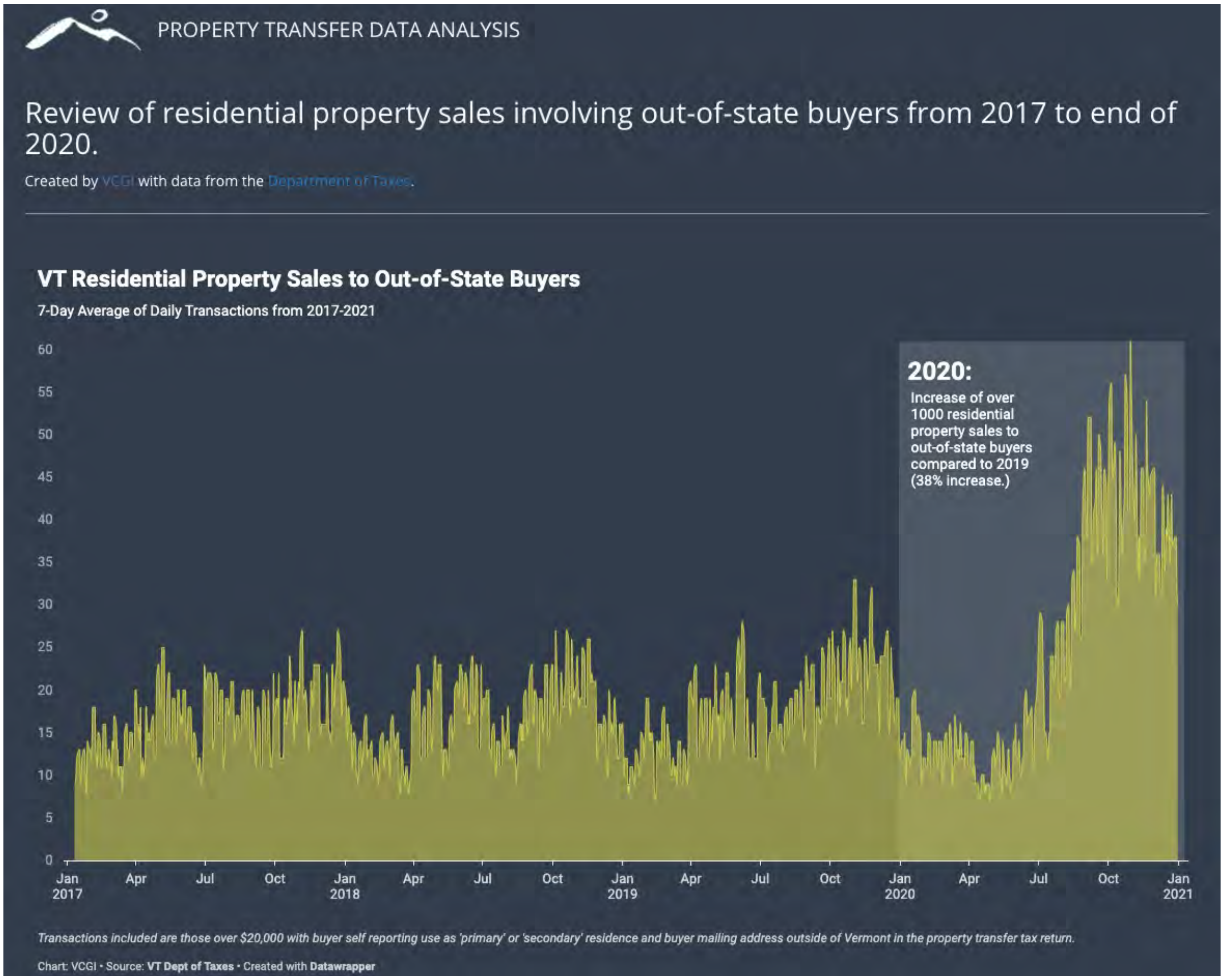


Figure 9-1: Vermont housing sales since 2017 to out-of-state buyers. Graphic created by VCGI with data from the Department of Taxes (VCGI, 2021)

COVID-19-related migration also had an impact on housing prices. A cross-city analysis (Honolulu, Houston, Santa Clara, Irvine, and Des Moines) of housing prices in the United States during the pandemic found that only Honolulu showed a decrease in housing prices. Houston, Santa Clara, Irvine, and Des Moines all had housing price increases (Wang, 2021). Given this data, it is possible that climate migration may exacerbate Vermont's existing "crisis of affordability" (Heintz, 2020), however, future research is needed.

Urban flight (i.e., people fleeing urban areas during the pandemic to avoid high transmission rates of COVID-19) in the United States was largely by "younger, whiter, and wealthier" populations fleeing to areas to which they were socially connected (e.g., sheltering with family and friends or in second homes) (Coven et al., 2020, p. 1). Consequently, the regions receiving pandemic-migrants were shown to have higher cases of COVID-19, which suggests that “urban flight was a vector of disease spread” (Coven et al., 2020, p. 1).

Both the pandemic’s impact on housing prices and urban flight raise questions of equity about who is able to purchase a home and who is able to move out of more at-risk areas. Both questions are key to future planning surrounding climate change and climate migration. A Vermont Public Radio interview described how Vermont has too few homes for sale and how the uptick in home sales during the pandemic have led to affordability concerns (Wertlieb & Smith, 2021). The interview reported that buyers who were “super strong financially” and “out-of-state buyers who may be able to put more cash down, for example, than somebody who’s [already living] in-state” were often winning bids (Wertlieb & Smith, 2021). Higher-income populations were also more easily able to move out of less-desirable urban areas during the pandemic, and as a result, communities of color, who often had less agency and ability pick up and leave less-desirable circumstances, were impacted disproportionately by the pandemic (Golestaneh et al., 2020).

Vermont could consider the COVID-19 pandemic a glimpse into future climate migration events. Climate change does not often create brand-new challenges, it more often exacerbates existing challenges and inequities. Many questions and uncertainties remain about how climate migration will impact Vermont, so the pandemic could serve as a starting point for planning and future research.

8.4 INFRASTRUCTURE SYSTEMS AND THEIR INTERCONNECTIONS IN THE CONTEXT OF CLIMATE CHANGE

Vermont communities rely on infrastructure systems for their well-being. These systems, also called lifeline or critical infrastructure systems, are projected to be negatively impacted by climate change. This section applies a nexus approach to community development in Vermont. A nexus approach is a methodology in which systems’ interconnections are intentionally accounted for or investigated in the context of any research or planning endeavor, in this case, community development in the context of climate change. Applying a nexus approach in the context of implementing climate change adaptation and resiliency planning is important because the infrastructure systems on which communities rely do not operate in isolation; they have many interdependencies. The key infrastructure systems to consider in the context of community development and planning and climate change are water, transportation, communications, energy, food, and healthcare infrastructure. The following subsections highlight the key climate change impacts to each infrastructure system and the interconnections between systems that are most relevant to the state of Vermont.

Other Vermont Climate Assessment chapters cover individual systems in greater depth; the purpose here is to focus on aspects of the infrastructure systems relevant to community development and planning and introduce key infrastructure interconnections. Please refer to the Water Resources, Energy, Agriculture and Food Systems, and Human Health chapters for more information. Additionally, resources on flood resilience and critical infrastructure are available from the Department of Homeland Security (Department of Homeland Security, n.d.).

8.4.1 Water Infrastructure

In Vermont, 30% of households obtain drinking water from private wells (Vermont Department of Health, 2021a). Aside from newly dug wells, these water sources are not regulated by the state of Vermont or EPA. According to the 2019 Vermont Infrastructure Report Card, the state's drinking water system received a score of C- (mediocre), the stormwater system received a score of D+ (poor), the dams received a score of C (mediocre), and the wastewater system received a score of D+ (poor) (ASCE, 2019).

Following are concrete examples of how water infrastructure is critical to other infrastructures in the state.

- ***Water - Health***: Water and water quality are essential for human health and well-being. Disasters or flooding can disrupt the municipal water system, which can leave communities without water or without safe drinking water. For example, after Tropical

Storm Irene, many Vermonters were concerned about whether the flood waters and stormwater runoff had contaminated their well water. Neither the state nor EPA regulate well water testing, so it is important for individuals to be proactive about procuring testing (Vermont Department of Health, 2021a).

- ***Water - Energy***: The energy system often requires water for hydropower generation or geothermal ground source heating (Renewable Energy Vermont, 2021). Eighty-five hydroelectric generation facilities currently operate in Vermont and on its borders (State of Vermont, 2021e).

- ***Water - Economy***: A recent study found that phosphorus reduction in Lake Champlain would benefit the economy by increasing tourism and the value of real estate (Gourevitch et al., 2021). At Missisquoi Bay, alone the study estimates that eliminating phosphorus inputs would benefit tourism by $28.5 million and property sales by $11.2 million (Gourevitch et al., 2021).

- ***Water - Recreation***: Harmful algal blooms, which thrive under the warmer temperatures projected in Vermont under climate change, negatively impact lake tourism. As discussed further in the Water Resources chapter, harmful algal blooms cause many industries to shut down, and many tourist establishments cannot operate (e.g., an increase in the number of beach closure days).

8.4.2 Transportation Infrastructure

According to the 2019 Vermont Infrastructure Report Card, the state's bridges and roads each received a score of C+, which equates to *mediocre* (ASCE, 2019). As of 2017, Vermont had 14,174 miles of local and state roadways, 806 miles of the National Highway System, 2,709 miles of the State Highway System, and 139 miles of Class 1 town highways (ASCE, 2019). The damage from Tropical Storm Irene highlighted the vulnerabilities of the state's transportation system and inspired the Vermont Agency of Transportation (VTrans) to create the Vermont Transportation Resilience Planning Tool (TRPT) in 2019 (Esri et al., 2019). The Vermont TRPT seeks, "to improve the resilience of Vermont's highway network to floods and erosion by providing data and tools to inform planning and investment decisions.” Instead of only trying to recovery from damages as quickly as possible, the tool can be used to identify vulnerabilities to proactively reduce or avoid damages in the future (Schliff et al., 2018, p. 1).

Following are examples of how other infrastructure systems depend on the transportation infrastructure system.

- ***Transportation - Food***: The food system relies on the transportation system to distribute agriculture products and to resupply grocery stores, and the transportation system limits access to food when severe snow storms or extreme weather events block roads, and therefore access to food. Reflection of the deep connections between the food system and the transportation system makes it clear that there is an urgent need to examine supply chains in the context of climate change. Many cities and states rely on national and global supply chains, which can be threatened by climate change (Heard et al., 2017). As stated in the Vermont Agriculture and Food System Strategic Plan 2021–2030, “Bolstering short and reliable regional food supply chains will reduce our exposure to global food system disruptions and meet the needs of our most vulnerable communities” (Claro et al., 2021, p. 7). More information on the food system in Vermont is available in the Agriculture and Food Systems chapter.

- ***Transportation - Health***: Transportation infrastructure is linked to health in terms of the improved air quality potential resulting from switching to electric vehicles (EVs) and other alternative fuels to reduce emissions. Transportation is also critical to health in terms of ensuring transportation along supply chains of pharmaceuticals and other medical supplies and via access to healthcare facilities during a natural hazard or disaster.

- ***Transportation - Energy***: Blocked roads and damaged bridges following a disaster can limit the ability of response teams to reach and repair downed power lines and other energy system disruptions. A Seven Days article interviewed people in towns that had been cut off from transportation and energy during Tropical Storm Irene. One person reported, "'Bath told me she was supposed to start student teaching on Monday, but without electricity or a phone or a reliable way to get off the mountain, she's in a holding pattern.'" And, "'We're so cut off here. It could be a month before our electricity comes back on. It could be three days,' she said. 'It's just totally overwhelming.'"(Ober, 2011a).

- ***Transportation - Economy*****:** During disasters, particularly flood events, it is common for roadways to become impassible due to damage or blocked by debris. Employees may not be able to reach their workplaces due to transportation system disruptions, and supply chains can also be disrupted. For example, Tropical Storm Irene damaged the roads and bridges around the state and as a Seven Days article stated, "roads in and around Killington were swept away, isolating residents and businesses for weeks" (Levitt, 2012).

- ***Transportation - Environment****:* In Vermont, the transportation sector is the leading source of GHG emissions, mostly from private cars. In 2010, transportation was responsible for 51% of the city of Burlington's GHG emissions (Kelley, 2013).

8.4.3 Communications Infrastructure

- Many people in Vermont have access to broadband and internet, but a "digital divide" remains: currently, 60,000 homes lack broadband (McCallum, 2021b). Vermont is currently developing a ten-year telecommunications plan (State of Vermont, 2021a) that meets the new requirements for broadband deployment established by Act 79 (Vermont Pub. L. No. 79, H.513, 2019). Communications infrastructure can be impacted by climate change in several ways, including: increases in temperature and precipitation can impact wireless transmissions through reduced signal range and weakened quality, and disasters slow response and recovery by limiting access to infrastructure to conduct repairs. On the other hand, it is possible that climate change could stimulate innovation and "accelerate the rate of technology change" (Ospina et al., 2014, p. 23).

- ***Communications - Health and Emergency Preparedness***: Lack of communications can leave communities without the ability to request help, which can put health and safety in jeopardy. Lack of communications can also interrupt response and recovery efforts following a disaster. Conversely, a study of healthcare workers in Vermont and New York following Tropical Storm Irene and Hurricane Sandy reported that "response and service organizations had to counter false information, rumor, and speculation while attempting to reach populations that lacked electricity, internet, and phone service. A noted dual challenge was how to provide continuous, needed information from a source that could be accessible should utilities go out and how to ensure that the public knew about this information source ahead of the disaster" (Walsh et al., 2015, p. 157). According to a *Seven Days* article, "After [Tropical Storm Irene], many Bethel residents were unable to access emergency information about their town, Nikolaidis explains. Her own family didn't have power or telephone service for five days; cut off from town by the washed-out road, they knew little about what was happening in the village" (Picard, 2014). In response, the Vermont Council on Rural Development launched the Digital Economy Project, which aims to build resilience through providing digital infrastructure to Vermont towns that previously lacked it (Picard, 2014; Vermont Council on Rural Development, n.d.-d). The Digital Economy Project has "delivered Front Porch Forum to every town in Vermont, created twenty-six free Wi-Fi zones/hotspots and twenty-five new municipal websites, and advised over 120 nonprofits and 260 small businesses" (Vermont Council on Rural Development, n.d.-d).

- ***Communications - Economy***: As the pandemic showed, many jobs, representing a strong portion of the economy, rely on communications infrastructure. Additionally, having an online business presence, such as a website, can increase businesses' resiliency. For example, Rochester, Vermont was isolated with no power or services for a week following Tropical Storm Irene. Beth Frock, owner of Boysenberry Smart Clothes in Rochester, found no outside traffic, even once basic services had been restored. This caused Frock to obtain a part-time job to make ends meet (Ripley, n.d.). In response, the Vermont Small Business Development Center, a partner in the Vermont Digital

Economy Project, assisted Frock in creating a website for Boysenberry Smart Clothes so that her company can remain competitive even when there are local disruptions (Ripley, n.d.).

8.4.4 Energy Infrastructure

The connections between the energy system and climate change are clear: energy sources are a significant contributor of CO_2 emissions. There are three types of electric utilities in Vermont: investor-owned, municipal electric departments, and member-owned rural electric cooperatives (State of Vermont, 2017). According to the 2019 Vermont Infrastructure Report Card, the state's energy system received a score of B-, which equates to *good* (ASCE, 2019). Current transmission lines are not able to accommodate the increases in renewable energy sources that are being deployed across the state, a key challenge (McCallum, 2021a).

- ***Energy - Food***: Most Vermonters purchase food from food retailers such as grocery stores. These retailers rely on the energy system to operate the buildings and refrigerate fresh and frozen food. With the projected increase in storm events, a loss of power can result in the closure of food retailers and consequent food spoilage. A Seven Days guide to preparing for Hurricane Sandy recommends, “Set your refrigerator and freezer to their coldest settings (remember to reset them back to normal once power is restored). During an outage, do not open the refrigerator or freezer door unnecessarily. Food can stay cold in a full refrigerator for up to twenty-four hours and in a well-packed freezer for forty-eight hours (twenty-four hours if it is half-packed)” (Picard, 2012).

- ***Energy - Water***: Power outages can cause disruptions in water treatment plants and the ability to pump water, including from private wells. A Seven Days guide to preparing for Hurricane Sandy suggests, “If your water supply could be affected by a power outage (a well-water pump system), fill your bathtub and spare containers with water. Water in the bathtub should be used for sanitation purposes only, not as drinking water. Pouring a pail of water from the tub directly into the bowl can flush a toilet” (Picard, 2012).

- ***Energy - Transportation***: A power outage can disrupt traffic signals and charging infrastructure for electric vehicles. Also, power is required to pump fuel at gas stations, so lack of power can disrupt the ability to operate vehicles. For more information about the links between energy and transportation, see the discussion of vehicle electrification in the Energy chapter.

- ***Energy - Health***: Increasing adoption of renewable energy sources and energy efficiency technologies will help reduce GHG emissions and improve air quality. Also, many services that are critical to health (such as hospitals, food retailers, and water treatment facilities) rely on power to function. Loss of power to these critical facilities can lead to food and waterborne illnesses and limit access to health care. Loss of power in winter can cause hypothermia. Loss of power in summer heat can lead to heat exhaustion. For more information on the health impacts related to the energy system and GHG emissions, see the Human Health chapter.

- ***Energy - Communications***: Power outages can disable or disrupt communications systems, such as internet access and cell service. The lack of digital communication can impact emergency response. In a study of the multifunctionality of country stores in Vermont, interviewees noted that their local country stores served as central hubs. With power out for almost a week during Tropical Storm Irene, people could not get information without power or internet, so the stores ran generators and served as important hubs (Morse, 2018).

- ***Energy - Environment***: Non-renewable forms of energy generation impacts the environment through GHG emissions. Switching to renewable sources of energy has environmental co-benefits in terms of air quality improvements and GHG reductions. Additionally, the energy system can have additional negative impacts to the environment during disasters. For example, flooding caused by Tropical Storm Irene ruptured a fuel tank in a municipal office building in Waterbury, turning “the basement into an oily pool” (Remsen, 2015).

- ***Energy - Economy***: Vermont has seen an increase in solar panel and array deployment, benefitting the environment through reduced GHG emissions and supporting the economy. Kelley and Flagge (2014) summarize, “Vermont's solar sector also rests on a firm foundation: the net-metering program that the legislature put in place seventeen years ago. Net metering enables users of renewable energy to get credit for the excess power their systems contribute to the state's electrical grid. Solar currently accounts for more than 90% of the energy homes and businesses are selling back to utilities.”

8.4.5 Food Infrastructure

The Agriculture and Food Systems chapter discusses the food system in detail primarily in terms of production. The focus in this Community Development chapter is the impact of climate change on food retailers, known as critical commercial services in academic literature. There is a strong culture of prioritizing locally grown and made products, which represent 13.9% of food purchases in Vermont (Claro et al., 2021, p. 5). The Vermont Agriculture and Food System Strategic Plan 2021–2030, released in February 2021, “confirms the need to prioritize our agricultural land base, infrastructure, and food security in order to increase Vermont farm and food system resilience to the impacts of climate change” (Claro et al., 2021, p. 7).

- ***Food + Water - Health***: Vermonters do not just rely on food broadly, they require access to fresh, healthy food for their well-being. The food system is linked to health in terms of power outages limiting refrigeration and water treatment during extreme events, which can lead to food and waterborne illness (Romero-Lankao & Norton, 2018).

- ***Food - Economy***: Vermont is America’s leading producer of maple syrup. A report by the United States Department of Agriculture shows that Vermont’s maple syrup production was 21% lower in 2021 than in 2020, a result of weather changes related to climate change (National Agricultural Statistics Service et al., 2021).

- ***Food - Environment***: Agricultural runoff and GHG emissions can negatively impact the environment. The Vermont Agriculture and Food System Strategic Plan 2021–2030 provides goals and objectives for how to improve farm stewardship to improve water quality. For example, there are specific methods and targets to ensure that agricultural pollutants do not exceed the Total Maximum Daily Load (TMDL) of phosphorus runoff into Lake Champlain (Claro et al., 2021).

- ***Food - Energy***: One way to reduce GHG emissions and increase renewable energy sources is to use waste from food and agriculture as organic material for biofuel generation. For example, the Energy chapter describes how Vermont has a "Cow Power" program, which seeks to capture methane produced from manure to burn as biofuel to generate electricity (Green Mountain Power, 2020).

8.4.6 Healthcare Infrastructure & Health

The Vermont Department of Health summarizes hospital infrastructure in the state: "There are fourteen non-profit hospitals and network of health care systems spread throughout Vermont including: eight small critical access hospitals, five mid-size rural hospitals, two academic medical centers, a Veterans Administration hospital, and five designated psychiatric inpatient facilities" (Vermont Department of Health, 2021b). Vermont hospitals and other healthcare facilities are susceptible to flood damage and rely on other systems to remain operational, including transportation for people to access the facilities, energy and water systems to run the facilities, and food to feed patients. Severe weather events can cause a breakdown in these infrastructures. For example, during Tropical Storm Irene, the state complex was inundated by flood waters, which "forced the emergency evacuation of fifty-one psychiatric patients—but not before they spent the night in the dark on the top floors of the state hospital with emergency fire alarms blaring for hours" (Remsen, 2015).

- ***Health - Environment***: Health can be impacted by air quality, increased heat, increased disease vectors (e.g., ticks and mosquitos), increased harmful algal blooms, and threats to drinking water from flood damage or hazardous spills. See the Human Health chapter for more detailed information on how the changing environment will impact the health of Vermonters.

- ***Health - Economy***: The economy depends on a healthy workforce. Additionally, healthcare is the most prominent industry in Vermont, employing approximately 50,000 residents (International Lake Champlain-Richelieu River Study Board, 2019).

8.4.7 The Economic System

Climate change-related disasters have varied effects on the economy. For example, following Tropical Storm Irene, "jobless claims nearly doubled in the first two weeks after the storm, peaking at 1,179 on September 3. Hard-hit Killington Resort initially filed a mass claim for 300 displaced employees but was able to put many of them back to work within a few weeks … . [...] On the other hand, the devastation created a surge in demand for construction work—the industry hardest hit during the recession in Vermont. Between 2007 and 2010, almost a fifth of all construction jobs in the state disappeared. Labor officials estimate 400 workers are presently employed rebuilding roads, bridges and flood-damaged structures" (Bromage, 2011). A "Stuck in Vermont" broadcast from Seven Days reporting on Wilmington, Vermont one month after Tropical Storm Irene found that the small town had more than forty flood-damaged businesses and 120 flood-related job losses; for such a small town, Irene nearly destroyed its economic center (Sollberger, 2011).

- ***Economy - Water Quality***: Harmful algal blooms, a proliferation of cyanobacteria that causes poor (or dangerous) water quality, reduced property values for shoreline properties in St. Albans Bay. The town of Georgia lowered the property values of thirty-seven lakefront properties by $50,000 each due to the blue green algae found in their waterfront (Hallenbeck, 2015). Harmful algal blooms can leave the lake unusable for recreation, which reduces the appeal of lakefront living (Hallenbeck, 2015). For more information on the health impacts of harmful algal blooms, see the Human Health chapter and for more information on water quality, see the Water Resources chapter.

- ***Economy - Floodplains***: A study of Otter Creek wetlands and floodplains in Middlebury, Vermont found that the floodplains reduce flood damages by 54—78%, with an annual value of flood mitigation services between $126,000 and $450,000 (Watson et al., 2016).

- ***Economy - Crop Production***: A United States Department of Agriculture report on crop production shows that Vermont's maple syrup production is down 21% compared to 2020 due to climate-related changes (NASS, 2021).
- ***Economy - Disaster Displacement:*** In an economic impact assessment of Tropical Storm Irene, it was estimated that Washington County would lose $32.7 million in income from the decrease of spending within the county due to relocated workers (U.S. Department of Commerce, 2012).

8.4.8 Social infrastructure

Social infrastructure, also called civic infrastructure or social cohesion, has been shown to strengthen communities and be a key contributor to community resilience (Chriest & Niles, 2018). Social infrastructure, or social capital, is classified as either "bridging" or "bonding." Bridging social capital improves intergroup linkages, where bonding social capital benefits intragroup linkages (Manyena et al., 2019). Project 14 is an initiative through the University of Vermont that connects student researchers with local newspapers with the goal of improving local news coverage and information-sharing in target areas throughout the state (University of Vermont, n.d.). Reilly (2021) describes a strong basis for information-sharing in the state: "Vermont already has many of the pieces in place for these efforts to make an impact, from strong media organizations like VPR, VTDigger and Seven Days, to active local governments, one of the highest rates of citizen volunteerism in the country, and a legislature and governor who are willing to work together to solve our challenges." Vermont author Bill McKibben credits Vermont's social cohesion as a reason that residents were initially receptive of economic closures and social precautions of the COVID-19 pandemic. He writes, "Vermonters entered the pandemic with remarkably high levels of social trust," and notes, "The state motto is 'Freedom and Unity,' and there's no question that, for the duration, Vermont's emphasis is on the latter" (McKibben, 2020).

- ***Social infrastructure - Economy***: A 2013 report on civic health and the economy states that factors such as social cohesion were predictors of a community's ability to withstand unemployment, such as during a recession (Levine & Kawashima-Ginsberg, 2013) or after a flood. Likewise, social cohesion can be useful in times of climate-related disasters (e.g., floods).

- ***Social infrastructure - Disaster Recovery***: A study of social capital following Tropical Storm Irene in Vermont revealed that "the strength and success of Vermont's recovery can be attributed to the combination and coordination between different types of social capital inherent of informal community efforts and the formal disaster framework" (Consoer & Milman, 2016, p. 171). For example, after over 700 residences had been destroyed or damaged by Irene flood waters, at least sixty second homeowners offered their vacation homes or condos to flood victims (Ober, 2011b).

- ***Social infrastructure - Food Security***: A study of social capital in rural Vermont following Tropical Storm Irene found that "rural communities with high levels of social capital display resilience and adaptation to food insecurity after extreme weather events" (Chriest & Niles, 2018). For example, residents of Moretown, Vermont organized a "meal train" in the aftermath of Tropical Storm Irene to help feed flood victims (Ober, 2011c).

8.4.9 Systems Interconnections as Co-Benefits

There are not only potential negative, cascading impacts between different systems; it is also important to consider potential positive "co-benefits" that can result between connected systems. Many resilience, adaptation, sustainability, or mitigation efforts can provide benefits far beyond the initial action or project. Considering the co-benefits of an effort can help actualize the true return on investment.

8.4.9.1 Example: Urban Forestry

Systems interconnections can be viewed as both negative, cascading impacts (as described above) where damage to one system negatively impacts the other systems to which it is connected and as positive co-benefits, in which changes to one system will benefit or improve the other systems to which it is connected. In the context of community development, urban forestry is a great example of how changes in one system (here, forestry) can provide positive changes in other systems.

Tree cover has been shown to improve air quality, help with the negative impacts of increased or extreme heat (such as the urban heat island effect), reduce flood impacts and improve water quality, and reduce energy costs through increased shading (see the Climate Change in Forests chapter for more information). Additionally, forests and tree cover have been shown to connect to diversity, equity, inclusion, and justice in that lower-income communities are more often associated with less tree cover, which deprives them of the many benefits listed in the prior sentence. As such, several cities in the United States have designed actions to build resilience around forests and tree cover; some examples are described below.

- **Trees for water quality**: Honolulu has an action entitled, “Minimize Economic and Property Risk within the Ala Wai Canal Watershed” (City and County of Honolulu, 2019, p. 100), which includes protecting forests as a method of addressing water quality and ecosystem health.
- **Trees for urban cooling**: To promote cooling, Honolulu has an action entitled, “Keep O ‘ahu Cool by Maintaining and Enhancing the Community Forest” (City and County of Honolulu, 2019, p. 98), and Los Angeles has an action entitled, “Develop and launch a neighborhood retrofit pilot program to test cooling strategies that prepare for higher temperatures” (City of Los Angeles, 2018, p. 70), which seeks to promote cooling through increased vegetation and tree plantings.
- **Trees for equity**: To ensure that the benefits of tree cover are equitably distributed, Los Angeles has an action entitled, “Plant trees in communities with fewer trees to grow a more equitable tree canopy by 2028” (City of Los Angeles, 2018, p. 73) and another entitled, “Increase access to open space in underserved neighborhoods” (City of Los Angeles, 2018, p. 80).

In summary, several cities highlight the importance of forests and tree cover to increasing community resilience in the context of climate change. Vermont should consider community tree cover (increasing it, conserving it, ensuring its equitable distribution) as a method of improving air and water quality, reducing flood impacts, and reducing energy use through tree cover shading (which reduces use of air conditioners). Increasingly these strategies may be developed at the local level with support from state agencies or non-governmental organizations (see Climate Change in Forests Chapter).

8.4.9.2 Example: Food-Energy-Water Nexus

A classic example of co-benefits is the potential benefits associated with linking food, energy, and water systems (known as the food-energy-water nexus in academic literature). For example, prior to Magic Hat Brewing's move from South Burlington to New York, the brewery had installed a digester that was able to turn waste from the beer-making process (food) into energy through the use of a biodigester (McCallum, 2021a). Recently, an article by Seven Days (McCallum, 2021a) described how Franklin Foods plant, which produced Hahn's, a cream cheese, was looking into using the protein-laden wastewater from the cheese making process in an on-site digester to create methane, an energy source. With Franklin Foods, the potential lies in reusing protein-rich wastewater that the local wastewater treatment system did not have the capacity to treat and creating a local renewable energy source. The limitation was that the energy grid was not able to sustain another source of renewable energy.

8.4.9.3 Example: Vermont Council on Rural Development's Climate Economy Initiative

The Vermont Council on Rural Development (VCRD) has a Climate Economy Initiative, which seeks to promote the economic opportunity that results from the need for strategies that reduce energy use and carbon emissions (Vermont Council on Rural Development, n.d.-c). The initiative postulates that the climate change challenge of needing to reduce energy use and the associated carbon emissions can produce co-benefits in terms of stimulating green economic growth. For example, Grassroots Solar and Harry Hunt Architects are two Vermont businesses that embrace green economic growth as a co-benefit to climate action. Grassroots Solar, a solar company in Dorset, Vermont, seeks to help customers achieve energy independence through solar installations. Harry Hunt Architects, an architecture firm in Stowe, Vermont designs low-carbon homes ,so that less energy is needed for heating and cooling (Vermont Council on Rural Development, n.d.-a, n.d.-b). For more information, there is a "Progress for Vermont" report and action plan from the Vermont Climate Change Economy Council, which was founded by the VCRD (Vermont Climate Change Economy Council, 2016). This report makes recommendations for how the state can stimulate economic activity while addressing climate change.

8.4.9.4 Example: Water Quality Benefits to Implementing Flood Mitigation

A classic example of co-benefits is ecosystem services, the natural, non-monetary benefits associated with ecosystems and the natural environment. Protecting and conserving floodplains, wetlands, and forests (all examples of natural infrastructures) serve to both mitigate flood impacts and improve water quality (Singh et al., 2018). For example, wetlands provide ecosystem services in the form of flood attenuation and carbon storage, and they absorb phosphorus that can lead to degraded water quality (Singh et al., 2019). Additionally, in a study of open space protection and flood mitigation in the United States, open space preservation improve flood mitigation and improve water quality, and property values were increased along the perimeter of the preserved areas (Brody & Highfield, 2013).

8.4.10 Infrastructure Interconnections in the Context of Disasters

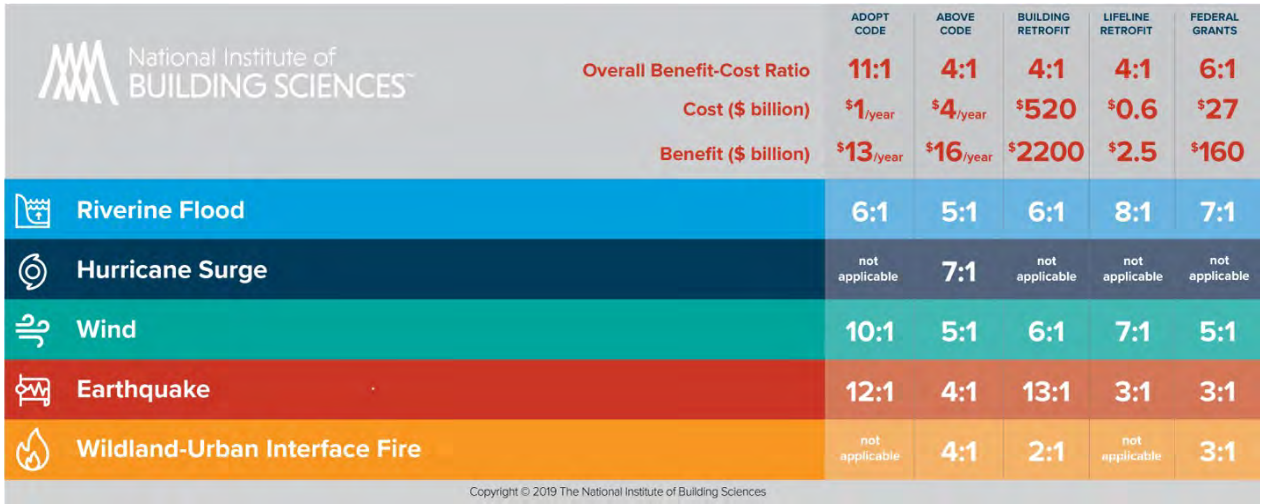
As described above, one of the most likely climate change impacts to face the state of Vermont is an increase in the frequency and severity of flood events. Given this likely scenario, this section describes systems interdependencies that have been noted in academic literature during flood and hurricane events. The objective is to demonstrate how systems interdependencies are relevant to Vermont and how they should be accounted for in relevant state, regional, or community planning.

The literature has highlighted how damage to the energy (de Bruijn et al., 2019) and transportation systems during a flood or other acute event will negatively impact nearly all other systems to which they are connected (Raub, Stepenuck, & Panikkar, 2021). For example, during the 2013 flood in Boulder, Colorado, six of the seven key roads adjacent to creeks became impassable, and the flood waters damaged the energy system, causing a power outage (Romero-Lankao & Norton, 2018). The lack of power resulted in many Boulder residents throwing away spoiled food due to the lack of refrigeration, and the damaged transportation system prevented deliveries, resulting in food shortages in the flooded area (Romero-Lankao & Norton, 2018). In a study of a hypothetical flood event in Florida, blocked roads were shown to limit access to food, reduce access to downed power lines for repair, and prevent the evacuation of those in severely impacted areas (de Bruijn et al., 2019). Food and water were also shown to impact health in that the lack of power for refrigeration and sanitation increased the prevalence of food and waterborne illnesses (Romero-Lankao & Norton, 2018).

Some mitigating factors in Boulder included use of radios and landlines when the communications system went down due to the power outage and use of a backup generator in a wastewater treatment plant that otherwise had lost power due to the power outage (Romero-Lankao & Norton, 2018). In a simulated hurricane, intentionally increasing the inventory at grocery stores and other critical commercial services in anticipation of a medium-scale (Category 3) hurricane event can reduce disruptions to food access in the surrounding community (Ni et al., 2019).

In Vermont, Tropical Storm Irene demonstrated the vulnerability of each infrastructure system cited as examples of interdependencies above. Tropical Storm Irene occurred on August 28, 2011 and caused extreme flood damage in Vermont, impacting 225 of Vermont's 251 towns (Anderson et al., 2020). Most notable was the damage to over 300 long-span bridges (Anderson et al., 2020). Additional damages included to state highway, municipal roads, and railroads, power outages to about 73,000 customers, Boil Water Notices in thirty public water systems, and hazardous waste and fuel spills (Pealer, 2012). The main office for Vermont Emergency Management in Waterbury was flooded, and thirteen communities were left with no passable roads to enter or exit the town (Pealer, 2012). Mobile home parks in the state were particularly hard hit; 154 mobile homes in parks were destroyed (Baker et al., 2014).

Prior studies demonstrate that pre-disaster planning and policy "result in lower disaster losses and serve to enhance community resilience" (Kim & Marcouiller, 2020, p. 1). A cost-benefit analysis of hazard mitigation found that $4 in future savings results from every $1 spent on infrastructure mitigation (Figure 9-2) (Multi-Hazard Mitigation Council, 2019).



National Institute of BUILDING SCIENCES™

	ADOPT CODE	ABOVE CODE	BUILDING RETROFIT	LIFELINE RETROFIT	FEDERAL GRANTS
Overall Benefit-Cost Ratio	11:1	4:1	4:1	4:1	6:1
Cost ($ billion)	$1/year	$4/year	$520	$0.6	$27
Benefit ($ billion)	$13/year	$16/year	$2200	$2.5	$160
Riverine Flood	6:1	5:1	6:1	8:1	7:1
Hurricane Surge	not applicable	7:1	not applicable	not applicable	not applicable
Wind	10:1	5:1	6:1	7:1	5:1
Earthquake	12:1	4:1	13:1	3:1	3:1
Wildland-Urban Interface Fire	not applicable	4:1	2:1	not applicable	3:1

Figure 9-2: Infographic by the National Institute of Building Sciences depicting the overall benefit-cost ratio of adopting up-to-date building codes in terms of hazard mitigation for riverine flooding, hurricane surge, wind, earthquakes, and fire (Multi-Hazard Mitigation Council, 2019)

Combining a systems interconnection (nexus) approach with the study of resilience is relatively new. For example, a systematic literature review found only twenty peer-reviewed academic studies that have combined the fields of coastal resilience (often in the context of flood or hurricane events) and a food-energy-water nexus approach (Raub, Stepenuck, & Panikkar, 2021). A document analysis of eleven United States city resilience plans found little evidence that a food-energy-water-transportation nexus had been applied in the development of the resilience plans (Raub et al., 2021). Although many emergency operations plans may use a coordinated approach, this has not spread to resilience planning per se. This serves as a call for future research and application.

8.5 VERMONT PLANNING IN THE FACE OF CLIMATE CHANGE

Planning is necessary to effectively account for current and future threats and conditions of any kind. Planning for the effects of climate change, such as from increased flooding, can reduce damages and better prepare for damages that cannot be avoided. Planning has been shown to be an important tool to build resilience and in emergency management (Burby et al., 1999; Cucuzza, Stoll, & Leslie, 2020; Nelson & French, 2002). The state and its communities are currently undertaking a variety of planning efforts in response to climate change. This section will cover the planning efforts at the state level, state and local-level land use planning, local-level hazard mitigation planning, and, finally, resilience planning and efforts to build community resilience.

8.5.1 Statewide Emergency Plans

Planning in Vermont occurs at multiple scales: state, regional, and local or community. At the statewide scale, Vermont has a State Emergency Management Plan and a State Mitigation Plan.

- The State Emergency Management Plan can be found here: https://vem.vermont.gov/plans/state.
- The 2018 FEMA-approved State Hazard Mitigation Plan (Vermont Emergency Management, 2018) can be found here https://vem.vermont.gov/plans/SHMP.

8.5.2 State and Local Level: Land Use Planning and Implementation

In Vermont, land use planning occurs at both the state and local levels, as described by Claro et al. (2021): “Vermont is divided among eleven regional planning commissions (RPCs), each with a regional land use plan, and as of 2017, 84% of Vermont municipalities had also adopted a municipal plan. State planning statutes require regional and municipal plans to include a land-use map and policies for preservation of natural and scenic resources, as well as sections on other topics related to the food system such as economic development, flood resilience, housing, and transportation” (p. 167). Land use planning is important in the context of climate change, as it can promote environmentally friendly outcomes and it can be essential in mitigating community flood risk. At the state level, Act 250 is the seminal land use regulation, and the state planning goals found in 24 VSA section 4302 are the main state land use regulations. Municipal plans and zoning and subdivision regulations are key to land use planning implementation at the local level. Increasing fragmentation of forests is a concern of many Vermonters, as discussed in the Climate Change in Forests chapter.

8.5.2.1 State Level: Act 250

Act 250 is the state-level Land Use and Development Law in Vermont. Act 250 was passed in 1970 with the intent to preserve the “environmental, social, and aesthetic character of the state in the face of development pressure” (Smith, Sandler, & Goralnik, 2013). This act requires that developers of projects of a certain size (e.g., commercial greater than ten acres) or number of housing units (e.g., residential with more than ten units within a five-mile radius) obtain a Land Use Permit from the District Environmental Commission, in addition to any local or subdivision permits (Geiger, n.d.). Small developments, including single homes on small parcels, may not be subject to Act 250 restrictions (see the Climate Change in Forests chapter for more on land use change). Act 250 requires development projects to meet ten criteria as related to (State of Vermont Natural Resources Board, 2021):

1. Water and air pollution
2. Water supply
3. Impact on water supply
4. Erosion and capacity of soil to hold water
5. Transportation
6. Educational services
7. Municipal services
8. Aesthetics, scenic, and natural beauty
9. Conforms to development and land use plans
10. Local and regional plans

8.5.2.2 Smart Growth Development

Smart Growth Development promotes compact development of settlements and urban centers that are separated by rural countryside, thus combating urban sprawl. Dense development can reduce total impervious surface in a municipality, reducing flood runoff. However, if not done well, stormwater concerns in urbanized areas can create local flash floods. Concentrating development in existing centers in Vermont also must be done with flooding in mind, as many of our developed areas were in flood-prone areas and continuing to invest in some of these areas is not prudent under increasing flooding.

- **Vermont Smart Growth Collaborative**: The Vermont Smart Growth Collaborative (Vermont Natural Resources Council, 2012) released the State of Vermont Smart Growth 2007 Progress Report, which examined state policies and spending between 2003 and 2006 (Levine et al., 2007). The 2021 update to the 2007 progress report will be available later in 2021 and will examine state policies and spending between 2013 and 2019 (Vermont Natural Resources Council, 2021).

- **Vermont Natural Resource Council efforts on smart growth**: The Vermont Natural Resources Council (VNRC) "promotes land use planning that creates communities that are environmentally sustainable, economically viable, and resilient" using smart growth principles. VNRC is in the Vermont Smart Growth Collaborative along with Conservation Law Foundation, Preservation Trust of Vermont, and others.

8.5.2.3 Local Level: Zoning

Planning can be implemented through the use of local zoning ordinances. For example, a study of zoning ordinances in 32 United States communities (of which, Burlington, Vermont was included) found that communities that included sustainability principles within their zoning ordinances were more likely to achieve sustainability than those that did not (Jepson & Haines, 2014). More specifically, zoning is an important tool to mitigate flood risk by regulating development in flood-prone areas. Zoning, often through ordinances, can "regulate the development of flood-prone areas, introduce building codes, convert built up areas to nature, relocate buildings, and raise public awareness, in order to lower flood risk" (Hudson & Botzen, 2019, p. 2). Zoning ordinances typically occur at the town level.

8.5.3 Local Hazard Mitigation and Local Emergency Management Planning

To be eligible for some federal grant funding through FEMA, communities can participate in the National Flood Insurance Program and adopt Local Hazard Mitigation Plans. Currently, Vermont communities have a total of thirty FEMA-approved Local Hazard Mitigation Plans (Two Rivers Ottauquechee Regional Commission, n.d.).

The State Emergency Management Plan mandates that all municipalities must review and update their Local Emergency Management Plan (LEMP) every year. These plans are required to access state post-disaster matching funding through ERAF (Emergency Relief and Assistance Fund). All municipalities qualify for a state match of 7%, but those with mitigation plans, LEMPs, adopted road and bridge standards, and participation in the National Flood Insurance Program can qualify for a 12.5% match. Those that also adopt river corridor regulations or that take part in FEMA’s Community Rating System can qualify for a 17.5% match. LEMPs are not publicly available, as they contain personal contact information; however, a template and other resources are available on the Vermont Emergency Management website (Department of Public Safety Vermont Emergency Management, 2021).

Box 9-1: Federal Funding via FEMA Grants

A study of how top-down flood mitigation strategies were implemented by southern Vermont communities found that “inadequate and poorly timed distribution of funding” was a barrier to implementing the suggested flood mitigation strategies (Paul & Milman, 2017, p. 14). This study suggests that state-mandated or suggested adaptation measures build in accessible funding mechanisms that can be accessed early in the implementation process (Paul & Milman, 2017).

FEMA provides several grant programs to help communities both prepare for and respond to hazards and emergencies. The following is an abbreviated list of FEMA grant programs available to Vermont communities. See FEMA (2021c) for a comprehensive list and details for how to apply.

- **Hazard Mitigation Assistance Grants**: Provides funding for removing or reducing risk prior to a disaster via the Hazard Mitigation Grant Program (HMGP); Building Resilient Infrastructure and Communities (BRIC), a new program as of September 2020 (FEMA, 2021a); Flood Mitigation Assistance (FMA) Grants; and Pre-Disaster Mitigation Grants.

- **Preparedness Grants**: These funds are for non-disaster-related efforts and include the Emergency Management Performance Grant Program, Assistance to Firefighters Grants Program, Homeland Security Grant Program, and many more (FEMA, 2021e).

- **Resilience Grants**: Available for dam safety and earthquake preparedness.

- **Emergency Food and Shelter Program**: This program provides assistance to ongoing local efforts to provide food, shelter, and other support services to those at risk of, or who are currently experiencing, hunger or homelessness (FEMA, 2021b).

8.5.4 Efforts to Build Community Resilience and Resilience Planning

Many communities across the United States have written, or are currently writing, plans for how they will build resilience against climate change and other shocks and stresses. While Vermont does not currently have a state resilience plan, it has undertaken several resilience building or measuring efforts and could consider writing a plan in the future. The state does have a Hazard Mitigation Plan, which has many of the characteristics of a natural hazard resilience plan (Vermont Emergency Management, 2018). "Climate change" is mentioned forty-seven times in the state plan. Climate change is not considered a direct hazard, but rather a driver of hazards such as floods, drought, ice-storms, etc.

Also, as is common in the emergency management field, planning and preparing for one disaster, if done well and holistically, increases resilience to other forms of disaster. For example, planning for structural collapse prepares for flood damage to homes. Preparing for structural fire prepares for post-flood fires (a common occurrence with woody debris and spilled fuel tanks). So, while a community may not be directly confronting climate change, it most likely is doing many resilience actions under another name. Lastly, good community planning creates resilience in that it is building community dialogue skills and a system for public information and decision-making. These are as essential as subject-specific plans in effective community planning.

8.5.4.1 Resilience Resources for Vermont Communities

- **Flood Resilience Checklist for Vermont Communities**: This checklist was created for those engaging in Municipal Plan updates, Hazard Mitigation Plans, and other planning efforts. Its objective is to increase a community's resilience (Vermont Department of Housing and Community Development, 2016).

- **Resilient Communities Scorecard**: The VNRC developed the Resilient Communities Scorecard (Vermont Natural Resources Council, 2013) to be a tool for Vermont communities to use in building resilient communities.

- **Resilient Vermont**: The Resilient Vermont Network “is a new collaboration of organizations and agencies in Vermont that are working to advance climate resilience. The Network is working to improve alignment, coordination, communication, and strategic impact across a range of issues related to climate resilience” (Resilient Vermont, n.d.). Resilient Vermont released a report entitled “Vermont’s Roadmap to Resilience” that provides recommendations for how to build resilience to climate change (Institute for Sustainable Communities, 2013).

- **Act 16 Flood Resilient Planning**: In 2013, Vermont created a flood resilience goal (V.S.A. 24, section 4302(c)14) and a flood resilience element for regional plans (V.S.A. 24, section 4348a(a)11) and municipal plans (V.S.A. 24, section 4382(a)12) through Act 16 (Vermont H. 401 Act 16, 2013). For plans adopted after July 1, 2014, Act 16 specifies that a flood resilience element must be incorporated within all municipal plans, and regional plans must meet the flood resilience elements and goals. Municipal plans seeking regional approval must also meet the state planning goal (V.S.A. 24, section 2450).

- **Flood Resilience Planning Resources:** The Central Vermont Regional Planning Commission provides a list of resources for flood resilience planning, including information for municipal plans, floodplain fact sheets, and fluvial erosion hazard maps and language (Central Vermont Regional Planning Commission, 2021).

- **Flood Ready Vermont**: Flood Ready Vermont provides a list of resources for municipalities seeking to write or update their Municipal Plans to include a flood resilience element (Flood Ready Vermont, 2021).

- **Vermont Planning Manual (https://accd.vermont.gov/community-development/town-future/municipal-planning-manual):** This is the main manual for municipal planning in Vermont. Many of the concepts of municipal planning, especially land use, natural resources, and capital budgeting, make a community resilient (State of Vermont Agency of Commerce and Community Development, 2021).

- **FEMA's Hazard Mitigation Planning:** FEMA has developed a process for planning to lessen the effects of natural hazards through the development of mitigation plans. This process is designed to meet federal guidelines for such a plan (FEMA, 2021d).
- **Vermont Department of Environmental Conservation Hazard Area Bylaws:** These are model bylaws available for communities that "have been pre-reviewed by FEMA and meet or exceed the requirements of the National Flood Insurance Program" (Vermont DEC, 2021).

8.6 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

Confidence level	**Very high**	**High**	**Medium**	**Low**
Description	Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus	Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

<u>Key Message 1:</u> Flooding is the most likely natural disaster to occur in Vermont and should be accounted for in all community development and planning efforts in the state. However, extremes will become more common, so planning should also account for chronic hazards, such as drought.	
Finding	There is a high confidence level that flooding will be the most likely disaster to occur in Vermont.
References	(FEMA, n.d.)

<u>Key Message 2:</u> Systems interconnections are essential to consider in community development and planning in the context of future climate change scenarios, particularly in the context of disasters.	
Finding	Medium confidence: Incorporating systems interconnections in the context of resilience and planning is relatively new, however, there is evidence to suggest it is important to continue.
References	(Raub, Stepenuck, & Panikkar, 2021; Raub et al., 2021)

<u>Key Message 3</u>: Vermont is expected to continue to have a favorable climate under future climate change projections, however, there is very little information to predict if the state will face an influx of climate migration. Future research is needed.	
Finding	Low confidence: There is little information to predict how climate migration will impact Vermont; more research is needed.
References	(Tacy, Hanson, & Poulin, 2020)

<u>Key Message 4:</u> Vermont communities must engage in planning to access federal funding and to prepare for current and future climate change impacts, including population growth, flooding, and droughts.	
Finding	There is a very high confidence level that planning is essential to prepare communities for the impacts of climate change. Planning has shown to be an effective tool to build resilience and in emergency management.
References	(Burby et al., 1999; Cucuzza et al., 2020; Nelson & French, 2002)

<u>Key Message 5:</u> Climate change will not impact all communities equally; the needs and capacity of vulnerable populations should be considered with all community planning efforts.	
Finding	Very high confidence: It is well proven that climate change impacts are not equitably distributed. For example, in Vermont, trailer park communities were negatively impacted by flooding during Tropical Storm Irene.
References	(Adger, 2010; Baker, Hamshaw, & Hamshaw, 2014; Cutter et al., 2008; Shi et al., 2016; Thomas et al., 2013; Van Zandt et al., 2012)

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9 CARBON SEQUESTRATION IN AGRICULTURAL SOILS

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9.1 KEY MESSAGES

1. **The soil carbon sequestration potential of agricultural management practices in Vermont is uncertain and likely mediated by site-specific factors such as soil type, geography, land use history, and weather.** Climate change mitigation benefits are possible but not guaranteed from the use of common practices implemented to sequester carbon (such as cover cropping, conservation tillage, no-till, and rotational grazing) on Vermont agricultural lands. There is evidence, however, that these practices can improve soil health and increase farm resilience to climate change.
2. **Assigning carbon offsets or payments for climate mitigation services provided by Vermont agricultural lands based on practice adoption alone currently lacks a strong scientific foundation.** Further investigation and monitoring is needed to improve understanding of management practices and soil carbon sequestration, including field studies and modeling. Well-calibrated models, validated for application in Vermont, have potential for identifying relationships between management change(s) and carbon dynamics. Participatory research that engages the expertise and needs of farmers is necessary to assess the local impacts of best management practices and make projections into the future.
3. **Whole-system accounting is required to assess potential trade-offs and to determine net climate change mitigation benefits of soil management strategies.** Changes in soil carbon stocks at a given location are only one piece in climate mitigation accounting. In all cases where offsite carbon sources are being used to boost soil organic carbon, a broader life cycle assessment extending beyond the farm gate is needed that considers offsite carbon source removal, transport, and processing; alternative end uses of the carbon source; interactions with other soil GHG-producing processes; and synergies between the soil amendments and the input of *in situ* plant-derived carbon. It is critical to keep in mind the primary objective: increase the net transfer of CO_2-equivalents from atmosphere to land. Only strategies achieving this primary objective should be considered climate mitigation. Failing to account for other fluxes of carbon and greenhouse gases could result in unintended consequences due to trade-offs.

9.2 ADDITIONAL SUMMARY POINTS

- It is imperative to ground statewide climate mitigation efforts in Vermont firmly within the most recent scientific evidence and to highlight key scientific uncertainties and knowledge gaps that have policy implications.
- The soil carbon sequestration potential of agricultural management practices is inconsistent across the literature and is mediated by site-specific factors such as soil type, geography, land use history, and weather.
- More research is needed to improve understanding of how management practices affect both shallow (0-30 cm) and deeper (>30 cm) soil layers.
- Climate change mitigation benefits are possible but not guaranteed from the use of common practices implemented to sequester carbon (such as cover cropping, conservation tillage, no-till, and rotational grazing) on Vermont agricultural lands. However, there is consistent evidence that these practices improve soil health and increase farm resilience to climate change.
- Monitoring is necessary to quantify climate mitigation benefits of specific practices applied across multiple Vermont agricultural contexts.
- Well-calibrated models, validated using local data, hold promising potential to identify relationships between management change(s) in a particular context and ensuing change(s) in net C fluxes, but such models do not yet exist for application in Vermont.
- Assigning carbon offsets or payments for climate mitigation services provided by Vermont agricultural lands based on practice adoption alone currently lacks a reliable and consistent scientific foundation.
- Changes in soil carbon stocks are only one piece in climate mitigation accounting. Whole-system accounting is required to assess potential trade-offs and to determine net climate change mitigation benefits of soil management strategies.
- Farm resilience is vital, and farmers should be supported in implementing best management practices for improving financial and ecological resilience.

- Participatory research that engages the expertise and needs of farmers is necessary to assess the local impacts of best management practices and make projections into the future.

9.3 INTRODUCTION

Agricultural soil health has become an increasingly popular topic in Vermont and other New England states in the past 10 years. From scholarship (Jemison et al., 2019; Kersbergen, 2012; Bakelaar et al., 2016; Adair et al., 2019) to popular news coverage (Foster, 2021; Leslie, 2020), the topic is receiving considerable attention. Amidst the growing interest in soil health, there is a particular focus on the potential for agricultural soils to sequester atmospheric carbon and thereby contribute to the mitigation of climate change. In the State of Vermont's 2021 legislative session, bills were proposed to: establish a statewide definition of and commitment to soil health and implement carbon sequestration tax credits as part of a statewide payment for ecosystem services program. Interest in soil carbon was also evident in a 2020 survey administered as part of the UVM-ARS partnership. Survey respondents identified soil organic matter and active carbon as two of the five most important metrics for assessing soil health on Vermont's small- and medium-sized farms. Similarly, respondents identified interactions between soil health and climate as one of the top three research and outreach priorities for the University of Vermont (Neher et al., 2021).

Interest in agricultural soil carbon sequestration in Vermont is likely influenced by large-scale policies and initiatives established elsewhere. This includes the "4 per 1000 Initiative" for increasing soil organic carbon stocks, also known as "4 per mille" or "4‰," which was launched by the French Ministry of Agriculture in 2015 for the 21st Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC). This initiative aspires to increase global soil organic carbon stocks by 0.4% per year to offset the global emissions of greenhouse gases (GHGs) by anthropogenic sources. The initiative mainly focuses on agricultural soils with relatively low levels of soil organic carbon and encourages farm management practices that preserve and increase soil organic carbon stocks while limiting carbon trade-offs (Rumpel et al., 2020). While the goals of climate change mitigation and increasing soil organic carbon are certainly laudable, the 4 per 1000 Initiative has received significant criticism from several scientists (Poulton et al., 2018; Rumpel et al., 2020). The potential for "regenerative agriculture," which has been defined in various ways (Newton et al., 2020), to sequester carbon in soils and thereby serve as a climate mitigation tool has also been the focus of intense scientific debate. For example, the World Resources Institute recently posted a blog entitled "Regenerative Agriculture: Good for Soil Health, but Limited Potential to Mitigate Climate Change" (Ranganathan et al., 2020), which engendered both support (Powlson et al., 2020) and criticism (Paustian et al., 2020) from well-respected scientists. While these debates are particularly intense at the moment, they are not entirely new (e.g., Schlesinger, 2000).

It is imperative to ground climate mitigation efforts in Vermont firmly within the most recent scientific evidence and to highlight key scientific uncertainties and knowledge gaps that have policy implications. In this chapter, we first briefly describe the underlying biogeochemistry relevant to climate mitigation by agricultural soils. Second, we review evidence linking practices associated with "conservation agriculture" or "regenerative agriculture" with climate mitigation outcomes (carbon emissions, soil carbon storage, nitrogen emissions). Third, we discuss challenges related to measurement and potential payment schemes. Finally, we close with recommendations for future efforts in Vermont.

9.4 THE BIOGEOCHEMISTRY OF CLIMATE MITIGATION BY AGRICULTURAL SOILS

Soils' physical, chemical, and biological properties and processes are interconnected and can all be considered aspects of "soil health" (Moebius-Clune, 2016). This is especially important in the context of climate mitigation, for which the cycling of carbon and nitrogen is key. Biogeochemistry is a systems science related to the field of ecosystem ecology that integrates physics, chemistry, biology, and geology (Schlesinger and Bernhardt, 2013), providing a powerful lens for examining potential climate mitigation by agricultural soils. Using this lens, some key facts relevant to the assessment of climate mitigation by agricultural soils are:

- **Changes in soil organic carbon storage are driven by the balance between carbon inputs to and losses from the soil.** Carbon inputs to soils can include plant litter (shoots and roots), root exudates, and exogenous soil amendments (e.g., manure, compost, or biochar) (Basile-Doelsch et al., 2020). Carbon loss from soils mainly occurs as CO_2 resulting from autotrophic (roots) and heterotrophic (microorganisms and fauna) respiration, but can also include CH_4 emissions that result from methanogenesis under anaerobic conditions, leaching of dissolved organic carbon, and erosion (Basile-Doelsch et al., 2020).
- **There are two primary levers to increase soil organic carbon storage – increase C inputs and/or decrease C losses.** Increases in carbon inputs to agricultural soils can potentially be driven by improved crop rotations and increased crop residues, use of cover crops, conversion to perennial grasses or legumes, additions of manure, compost, or biochar, or improved grazing land management (Paustian et al., 2019). Decreases in carbon losses can potentially result from conversion to perennial grasses or legumes, using conservation or no tillage, or rewetting soils (Paustian et al., 2019).
- **Soil organic carbon storage does not necessarily increase linearly with increased C inputs – and there are limits.** While some long-term agricultural field studies have observed soil C stocks that appear linearly related to the amount of C returned to the system, others show little or no change in soil organic carbon in response to varying C input levels, or decreased soil organic carbon stabilization efficiency in high carbon soils compared to low carbon soils for the same treatment (Stewart et al., 2007). Saturation limits to soil organic carbon pools have been proposed or observed by various researchers with emphasis on certain mechanisms (Hassink, 1997; Baldock & Skjemstad, 2000; Stewart et al., 2007; Owen et al., 2015; Poulton et al., 2018). It may be possible to shift a soil's effective C stabilization capacity to some degree through changes in soil management (Stewart et al., 2007) and more research is needed to better understand the related mechanisms that determine limits on soil organic carbon

storage (Basile-Doelsch et al., 2020). Despite this uncertainty, it is generally agreed that the greatest potential for soil carbon sequestration exists on degraded soils with relatively depleted soil organic carbon (Lal, 2018; Amelung et al., 2020).

- **The cycling of other elements, particularly nitrogen and phosphorus, affects soil carbon storage and greenhouse gas emissions.** Nitrogen addition stimulates plant growth when N availability is a limiting factor and thereby increases C inputs to the soil (Huang et al., 2020). The same is true for phosphorus. These two elements (and others) must be available in the soil in adequate amounts to maintain crop productivity and resultant C inputs to the soil, which has led some to caution that ambitious global goals for carbon sequestration in agricultural soils will require vast inputs of N and P to soils (Van Groenigen et al., 2017; Spohn, 2020). Furthermore, nitrogen can be lost from agricultural soils as nitrous oxide (N_2O), an important greenhouse gas, which must be considered along with soil carbon storage and carbon emissions (CO_2, CH_4) in the determination of net climate mitigation benefits (Owen et al., 2015; Guenet et al., 2020).

9.5 THE AVAILABLE EVIDENCE LINKING PRACTICES TO CLIMATE MITIGATION

9.5.1 Croplands

The Nature Conservancy has recently created AgEvidence, a web-based tool to explore the impact of agricultural practices on crops and the environment (http://www.agevidence.org/, doi:10.5063/Z31X15). AgEvidence compiles evidence from numerous peer-reviewed field studies conducted in the US Midwest between 1980 and 2020 that focus on the links between agricultural practices and in-field response variables. All field trials included in AgEvidence focused on corn (including sweet corn), soybean, or both. For climate mitigation, AgEvidence includes studies examining the effects of cover crops and tillage. Figure 10-1 below summarizes 277 observations from twenty-seven studies on climate mitigation effects of cover cropping, including carbon emissions, carbon storage, and nitrogen emissions.

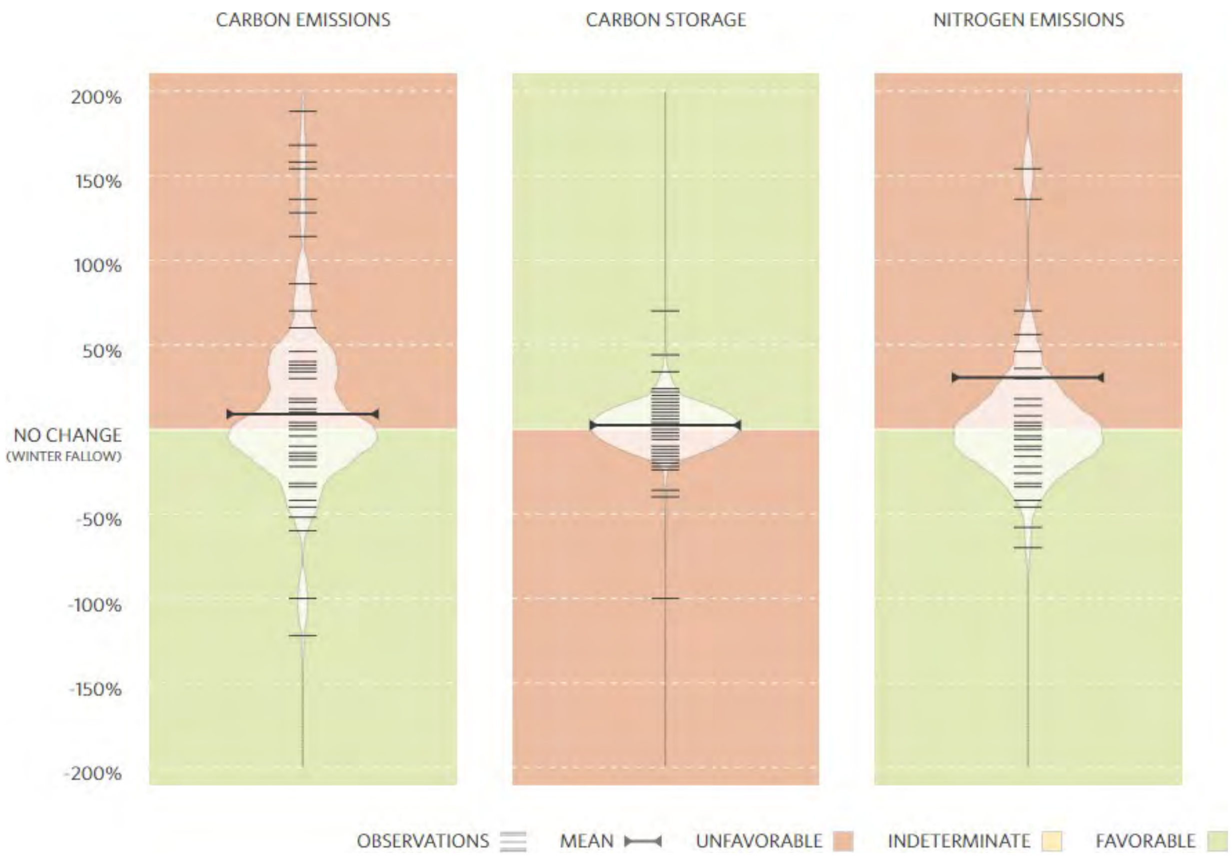

Figure 10-1: Observed percent changes on climate mitigation factors from using cover crops relative to the control in the AgEvidence database, including 277 observations from 27 studies (*http://www.agevidence.org/*, accessed May 9, 2021). Options selected in AgEvidence: study durations of 1 to 4+ years; single species; non-legume; soil sample depth = not measured, 0-30 cm, or 0-60 cm.

A companion “Insight” box on the AgEvidence website states that “cover crop studies show some potential for climate mitigation” and summarizes the evidence for cover crops and climate mitigation as follows:

- The use of single species, non-leguminous cover crops is associated with a 3% increase relative to the control for soil carbon on average. (Note: there are far fewer observations associated with multiple species cover cropping systems in AgEvidence).

- Soil carbon increases linked to cover crops are greater in topsoil (0-30 cm), whereas when the 0-60 cm depth was analyzed, changes in soil carbon linked to cover crops were neutral to slightly negative.
- Caution is warranted when interpreting nitrogen and carbon emissions in Figure 10-1. Further inspection of the data (see Figure 10-2 below) shows that cover crop usage is associated with no change in year-round N_2O emissions, while growing season measurements show an increase in N_2O with cover crops largely due to results from a single study where irrigation was present, which is known to increase N_2O emissions. Offseason N_2O emissions are also slightly increased with cover crops; however, this result was strongly influenced by a single study from a manure impacted soil. The study with irrigation also drives the pattern of higher CH_4 emissions with cover crops.

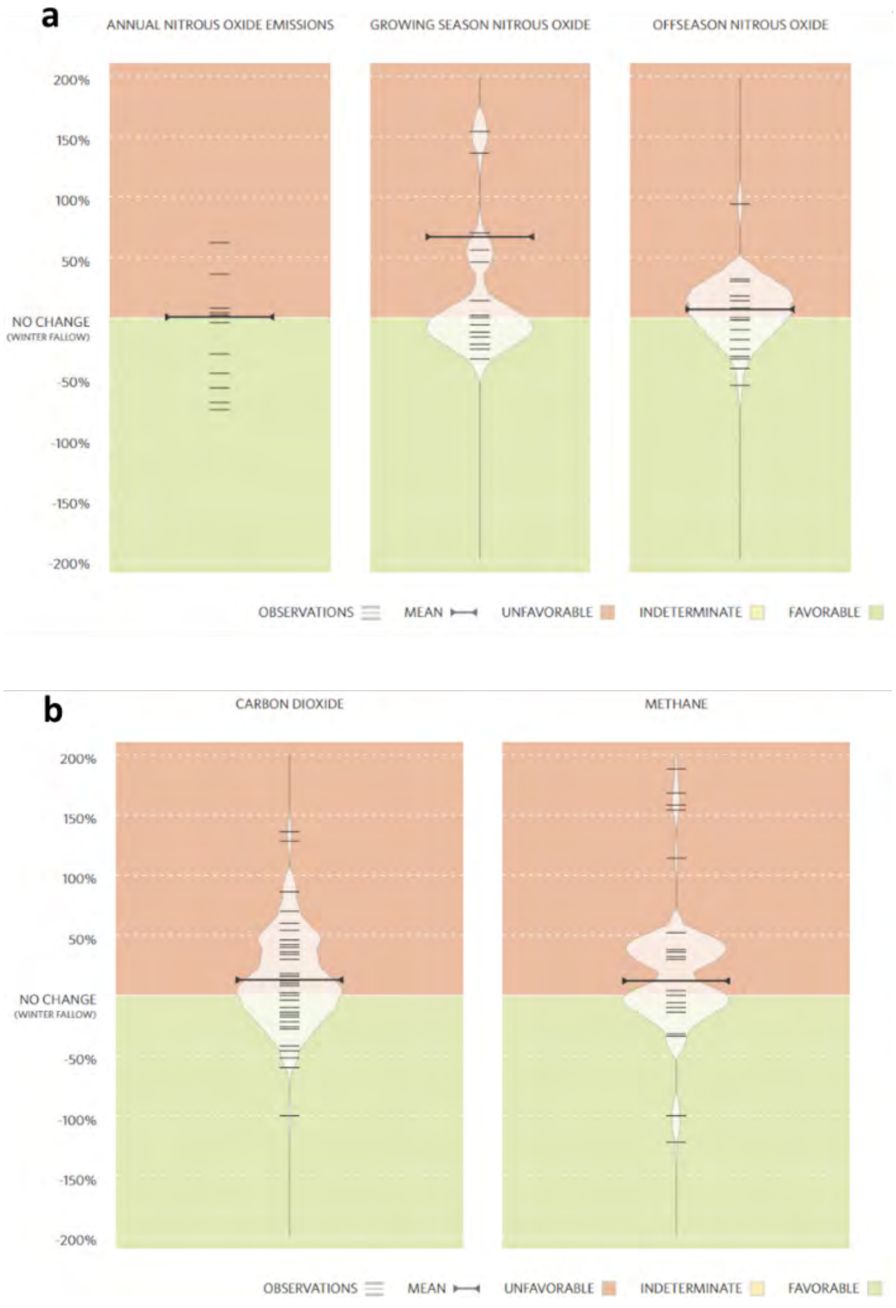

Figure 10-2: (a) Observed percent changes from cover cropping on nitrogen emissions relative to the control in the AgEvidence database, including 59 observations from 6 studies (*http://www.agevidence.org/*, accessed May 9, 2021). Options selected in AgEvidence: study durations of 2 to 4+ years; single species or two species; non-legume, non-legume mixture, or rotation of cover crops; soil sample depth = not measured. (b) Observed percent changes from cover crops on carbon emissions relative to the control in the AgEvidence database, including 72 observations from 4 studies (*http://www.agevidence.org/*, accessed May 9, 2021). Options selected in AgEvidence: study durations of 2 to 4+ years; single species; non-legume or rotation of cover crops; soil sample depth = not measured.

Some recently published global meta-analyses provide favorable results for the effect of cover crops on soil carbon storage. Poeplau and Don (2015) found that cover crop treatments had significantly higher soil organic carbon stocks compared to reference croplands, with an annual increase of 0.32 ± 0.08 Mg C ha^{-1} yr^{-1}. These findings have recently been used as the basis for large-scale estimates of climate mitigation by cover crops in Canada (Drever et al., 2021). However, the mean soil depth of sampling in the studies considered by Poeplau and Don (2015) was only 22 cm, indicating that their assessment could be optimistic given the less promising results in AgEvidence when deeper soils were included. Furthermore, many of the studies considered by Poeplau and Don were short-term (2-3 years), which is generally an insufficient time duration to assess changes in stable forms of soil organic carbon (Smith, 2004). Jian et al. (2020) found that including cover crops in rotations significantly increased soil organic carbon in near-surface soils by 15.5% and investigate the influence of climatic region, soil texture, cover crop types, cash crop types, and soil sampling depths. For example, they report that soil organic carbon increases were greatest for fine-textured soils. However, Jian et al.'s (2020) meta-analysis results were also largely influenced by short-term (< 5 years) studies of surface soils (0-30 cm), which suggests their conclusions could also be optimistic. More research is needed to clearly demonstrate the long-term effects of cover crops on soil carbon storage generally and within Vermont specifically.

Figure 10-3 below summarizes observations of tillage effects on climate mitigation, including carbon emissions, carbon storage, and nitrogen emissions. Effects of conservation tillage (Figure 10-3a) and no-till (Figure 10-3b) are shown separately. As with cover crops, a wide range in effects of conservation tillage or no tillage spanning from unfavorable to favorable has been reported in the peer-reviewed literature, with generally favorable mean changes relative to conventional tillage.

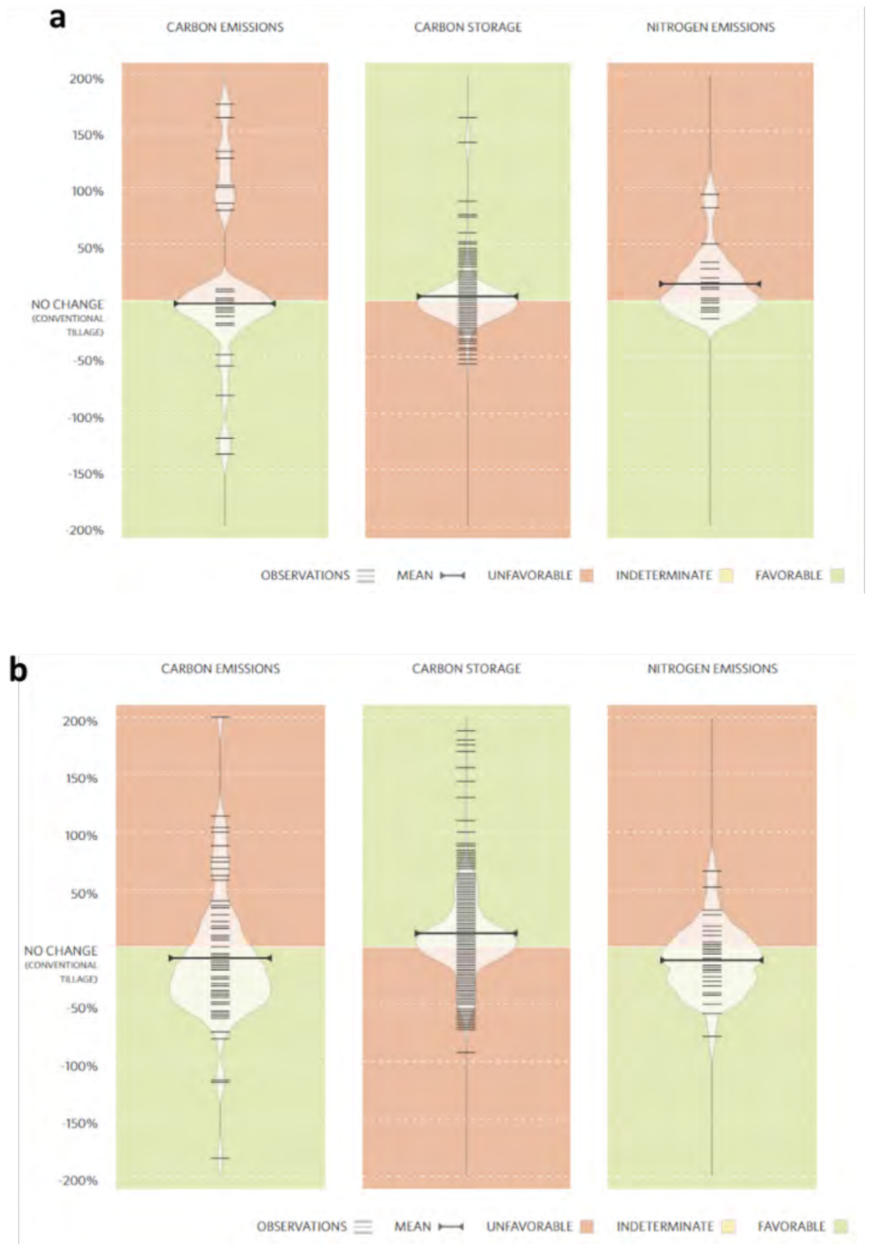

Figure 10-3: (a) Observed percent changes from conservation tillage on climate mitigation relative to conventional tillage in the AgEvidence database, including 488 observations from 28 studies (*http://www.agevidence.org/*, accessed May 9, 2021). Options selected in AgEvidence: study durations of 1 to 21+ years; control = conventional tillage; treatment = conservation tillage; soil sample depth = not measured, 0-30 cm, 0-60 cm, 0-100 cm, and 0-150 cm. (b) Observed percent changes from no-till on climate mitigation relative to conventional tillage in the AgEvidence database, including 870 observations from 50 studies (*http://www.agevidence.org/*, accessed May 9, 2021). Options selected in AgEvidence: study durations of 1 to 21+ years; control = conventional tillage; treatment = no tillage; soil sample depth = not measured, 0-30 cm, 0-60 cm, 0-100 cm, and 0-150 cm.

Based on the AgEvidence database, conservation tillage results in mean percent changes relative to conventional tillage of -2.6% (favorable) for carbon emissions, +3.7% (favorable) for carbon storage, and +14.7% (unfavorable) for nitrogen emissions. For comparison, no-till results in mean changes relative to conventional tillage of -9.7% (favorable) for carbon emissions, +11.8% (favorable) for carbon storage, and -11.7% (favorable) for nitrogen emissions. These results suggest that the benefits of no-till for climate mitigation are on average greater than those associated with conservation tillage. An "Insight" box on the AgEvidence website states, "No-till is associated with greater carbon storage, lower methane emissions, and lower growing season N_2O emissions" compared to conventional tillage. However, other researchers report evidence that in some cases increased N_2O emissions in no-till systems can offset the increased soil C storage when both fluxes are compared in CO_2-equivalents (Guenet et al., 2020).

One important methodological factor to consider in studies of no-till and soil carbon sequestration is the depth of soil considered in the analysis. Previous researchers have noted that observations of increased carbon storage based solely on measurements in the 0-30 cm soil layer can be misleading (Baker, 2007). This is due to the fact that crop roots often extend much deeper than 30 cm and increases in soil organic carbon (SOC) within surface soils may be accompanied by losses of SOC at greater depths (Baker, 2007; Luo et al., 2010; Powlson et al., 2014; Olson and Al-Kaisi, 2015; Slessarev et al., 2021). AgEvidence also lends some support to this concern, with the caveat that fewer studies have examined deeper soil layers (Figure 10-4). For the 41 studies in AgEvidence focused on the 0-30 cm soil layer, a mean change in soil carbon of +15.5% (favorable) for no-till relative to conventional tillage was observed (Figure 10-4a). However, the mean change in soil carbon for the 16 studies that examined 0-60 cm, 0-100 cm, or 0-150 cm soil layers drops to -0.3% (neutral/unfavorable) for no-till relative to conventional tillage (Figure 10-4b). Therefore, more research is needed to enhance understanding regarding how changes in tillage practice affect both shallow (0-30 cm) and deeper (>30 cm) soil layers.

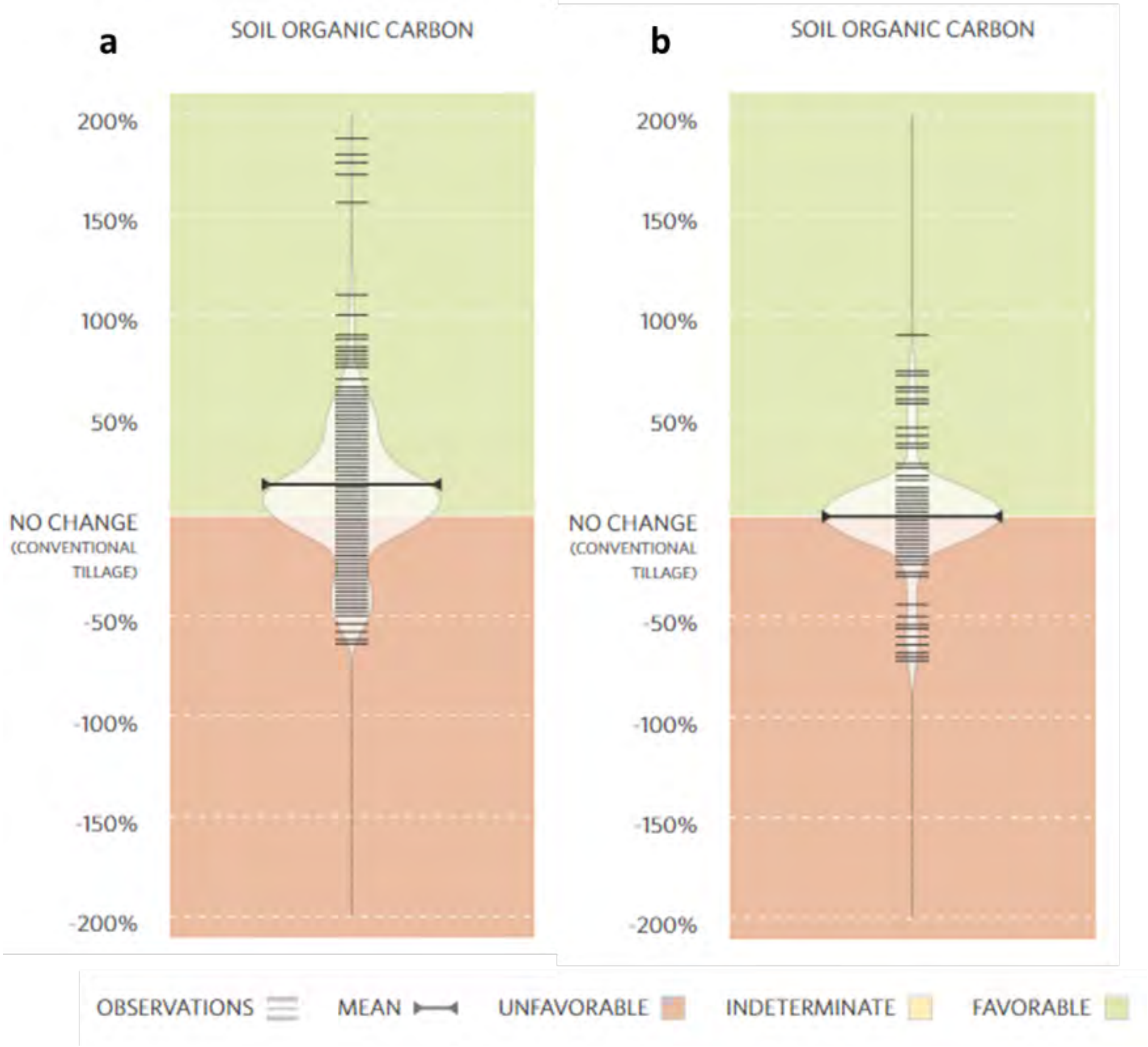

Figure 10-4: (a) Observed percent changes from no-till on soil carbon storage relative to conventional tillage in the AgEvidence database, including 491 observations from 41 studies focused on the 0-30 cm soil depth (*http://www.agevidence.org/*, accessed May 9, 2021). Options selected in AgEvidence: study durations of 1 to 21+ years; control = conventional tillage; treatment = no tillage; soil sample depth = 0-30 cm. (b) Observed percent changes from no-till on soil carbon storage relative to conventional tillage in the AgEvidence database, including 229 observations from 16 studies focused on 0-60 cm, 0-100 cm, or 0-150 cm soil depth (*http://www.agevidence.org/*, accessed May 9, 2021). Options selected in AgEvidence: study durations of 1 to 21+ years; control = conventional tillage; treatment = no tillage; soil sample depth = 0-60, 0-100, and 0-150 cm.

The data summarized by AgEvidence provide a useful starting point for assessing the potential climate mitigation effects of management practices on croplands in Vermont.

However, AgEvidence includes no data from Vermont and it is important to ask how the differences between Vermont and the Midwest, in terms of climate, soils, and other factors, might affect the climate change mitigation potential of various management practices. Unfortunately, we do not have enough local data to answer that question at this time. A search of peer-reviewed literature using Web-of-Science (terms: Vermont* soil* carbon*) on May 9, 2021, returned only one local agricultural field study. Dittmer et al. (2020) tested the effects of different management practices on GHG emissions in Alburgh, Vermont, over three growing seasons and found that: (a) no-till reduced CO_2 emissions but had no impact on N_2O emissions relative to vertical till, and (b) manure injection increased N_2O and CO_2 emissions, with the magnitude of this effect being greatest for 1 month post-application. We recommend that additional Vermont data be collected and systematically assessed in the future.

In summary, the evidence reviewed here collectively indicates that climate mitigation benefits are possible but not guaranteed from the use of common conservation practices (cover cropping, conservation tillage, no-till) on Vermont croplands. Inconsistency in the effects of practices on climate mitigation outcomes across studies could be influenced by numerous site-specific factors (time duration, weather, soils, other environmental factors, land management, and/or sampling methodology). The paucity of peer-reviewed Vermont evidence further increases uncertainty in the potential for climate mitigation from conservation practices on croplands in the state. ***Therefore, in the opinion of the authors, assigning carbon offsets or payments for climate mitigation services provided by croplands based on practice adoption alone in Vermont currently lacks a scientific foundation and should therefore be avoided unless new evidence becomes available. Monitoring is necessary to verify climate mitigation benefits.*** More discussion of monitoring is presented below.

Another potential strategy to boost soil organic carbon on Vermont croplands is the input of manure, compost, or biochar. It is clearly possible to build soil organic carbon in a field through the addition of manure or other organic amendments, which contain carbon themselves as well as nutrients that can stimulate plant growth resulting in conversion of atmospheric CO_2 into plant biomass C (e.g., Liang and MacKenzie, 1992; Poulton et al., 2018). However, taking a broader view beyond a single field, this practice does not necessarily result in a *net* sink for C in soils (i.e., additional transfer of carbon from atmosphere to soil) (Schlesinger, 2000). Adding more manure or compost to one field typically means adding less to another, thereby representing a reallocation of C between terrestrial locations. Biochar shows some promise for enhancing soil carbon sequestration in agriculture; however, biochar supply, cost, and uncertainty or time lags for climate mitigation benefits remain hurdles both locally and globally (Woolf et al., 2010; Shackley et al., 2014; Smith, 2016; Campbell et al., 2018). In all cases where off-site C sources are being used to boost soil organic carbon, a broader life cycle assessment extending beyond the farm gate is needed that considers off-site C source removal, transport, and processing; alternative end uses of the C source; interactions with other soil GHG-producing processes; and synergies between the soil amendments and the input of *in situ* plant-derived C (Paustian et al., 2016). ***It is critical to keep in mind the primary objective: increase the net transfer of CO_2-equivalents from atmosphere to land – only strategies achieving this primary objective should be considered climate mitigation.***

9.5.2 Grazing Lands

Grazing strategies, especially rotational grazing, are receiving increasing national and global interest as potential tools to sequester soil organic carbon and enhance soil health more broadly (Derner et al., 2016; Schulz et al., 2016), with ongoing debate centered on the potential benefits of grazing management to improve agricultural production and ecological outcomes (Roche et al., 2015). Rotational grazing strategies include, for example, high-intensity short duration grazing, “mob” grazing, and management-intensive grazing (Byrnes et al., 2018). Byrnes et al. (2018) conducted a global meta-analysis including 64 research articles to examine the effects of grazing strategy (i.e., no grazing, continuous grazing, rotational grazing), grazing intensity (light, moderate, heavy grazing), and site-specific environmental factors on three important aspects of soil health: soil carbon, nitrogen, and bulk density. Their results can be summarized as follows (Byrnes et al., 2018):

- Increased soil compaction occurs under all grazing strategies and intensities relative to no grazing.

- Rotational grazing strategies improved soil organic carbon and bulk density conditions over continuous grazing strategies.
- Greater continuous grazing intensity levels can negatively affect soil organic carbon.
- Site specific environmental factors underpin soil function and health responses to management.

Others have found that stocking rate, coupled with effective livestock distribution, is the single most important management variable influencing production and conservation goals in grazed ecosystems, outweighing other aspects of grazing strategy (Briske et al., 2011).

More research is needed to evaluate the climate mitigation potential of regenerative grazing systems, especially considering the multiple grazing approaches currently being explored by producers (e.g., holistic, adaptive, and other variants of rotational grazing). One challenge with such research is that adaptive grazing systems, by definition, are dynamic in response to varying weather and other environmental conditions that affect grassland productivity. It is therefore difficult to set up traditional replicated field experiments to compare different grazing systems at the landscape scale (Paustian et al., 2019; Teague et al., 2013).

Some recent evaluations find that climate mitigation estimates for regenerative grazing systems have been exaggerated (e.g., Nordborg, 2016), and others suggest some short-term promising results (Stanley et al., 2018; Mosier et al., 2021). A recent study by Rowntree et al. (2020) examined the ecosystem impacts and productive capacity of a multi-species pastured rotation (MSPR) livestock system at the well-known regenerative White Oak Pastures farm in Georgia, and report results that highlight some key points:

- First, implementation of the MSPR system on degraded cropland resulted in substantial soil carbon sequestration (a 5-fold increase in SOC stocks over 20 years) (Rowntree et al., 2020). While this is impressive, soil carbon gains following conversion of degraded cropland to pasture is not necessarily surprising given what is known about relative carbon storage across ecosystem types (Amelung et al., 2020). Furthermore, others have argued that, from a global perspective, opportunity to convert annual cropland to grazing is limited by the growing need for annual crops, noting that even if diet changes or yield gains could free up cropland, that land could sequester more carbon if restored to forest (Searchinger and Ranganathan, 2020).

- Second, when incorporating soil carbon sequestration, life cycle assessment indicated that the MSPR system emitted 4.1 kg CO_2-equivalent per kg of carcass weight, 66% lower than the comparative conventional commodity system (Rowntree et al., 2020). Although this constitutes a substantial reduction, the net GHG footprint of this MSPR system is still positive, drawing into question previous claims that the MSPR system has a ‘carbon negative footprint’ (White Oaks Pastures, 2019).
- Third, the MSPR system required 2.5 times more land compared to a conventional commodity system to produce the same amount of meat on a per carcass weight basis (Rowntree et al., 2020). The authors point out that the MSPR is well-suited for marginal lands, rather than productive lands suitable for higher value and more nutrient dense crops (Rowntree et al., 2020). However, it is again important to note the fact that such marginal lands could also be suitable for restoration to non-agricultural ecosystems that provide numerous ecological benefits (forests, wetlands). Agroforestry systems could be explored as well.

In a recent article entitled “Soil carbon sequestration in grazing systems: managing expectations,” Godde et al. (2020) summarizes the state of knowledge on grazing systems and climate mitigation as follows:

- Grazing systems emit greenhouse gases, which can be partly or entirely offset by soil carbon sequestration under specific agro-ecological conditions.
- Any soil carbon sequestration in grazing systems is time-limited and reversible.
- Protecting large carbon stocks in grazing lands is essential in order to avoid further CO_2 release.
- Soil carbon sequestration in grazing lands should be promoted in cases where it delivers environmental and agronomic benefits, including on degraded land.

- Caution should be applied for estimates of climate mitigation by C sequestration in grazing systems due to large uncertainties and dependence on economics, feasibility of implementation, and time frame considered.

9.6 MONITORING AND CONSIDERATIONS FOR PAYMENT SCHEMES

Despite the fact that measurement of soil carbon stocks in a single soil core sample is relatively straightforward, there are considerable challenges to accurately estimating changes in soil organic carbon stocks at field and farm scales. These include high spatial variability, changes in bulk density with changes in soil management, potential for redistribution of soil organic carbon between surface soils and deeper soils, and the slow rate of changes in bulk soil carbon (Smith et al., 2020; Slessarev et al., 2021). If feasible, soil organic carbon monitoring should include analysis of soils to at least 60 cm depth, and ideally to 100 cm depth (Liebig et al., 2010; Slessarev et al., 2021). However, measuring below 30 cm (the minimum recommended depth by IPCC; Ogle et al., 2019) can increase cost and require specialized equipment. It is not currently possible to verify sequestration rates that increase soil organic carbon stocks by <1% on an annual basis using direct soil measurements (Paustian et al., 2016; Smith et al., 2020). Therefore, longer study periods (ideally > 5 years) that extend beyond the timeline of most research grants are required to track changes in soil organic carbon (Smith et al., 2004). Measurement of total organic carbon by dry combustion is recommended, with steps taken to subtract any inorganic C present (Liebig et al., 2010; Nelson and Sommers, 1996). Researchers also commonly estimate soil organic matter using the loss on ignition (LOI) method (Nelson and Sommers, 1996). However, the relationship between LOI and soil organic carbon varies across soils and conversions between LOI and soil organic carbon should be validated using location- or soil-specific data (Konen et al., 2002).

There are some promising spectral methods emerging for direct point measurements in the field and lab (Smith et al., 2020). These include methods for measuring SOC concentration based on the reflectance of light on soil in the infrared region, where the organic bonds and minerals in the soil absorb light at specific wavelengths and SOC is predicted using a statistical model based on a spectral library (Smith et al., 2020 and citations within). In addition, laboratory costs could be reduced by using Fourier transform mid-infrared diffuse reflectance spectroscopy for estimation of total carbon, organic carbon, clay content, and sand fraction (Wijewardane et al., 2018). Remote sensing methods could also potentially be employed at scales not feasible with traditional or point spectral methods (Ge et al., 2011; Mulder et al., 2011). However, there are limitations of remote sensing, including limited penetration depth, limited duration of bare soil, and cloud cover (Smith et al., 2020). Furthermore, soil bulk density is a critical measure when estimating soil organic carbon stocks and cannot be estimated using remote sensing. Some techniques have been developed for estimating bulk density using gamma-ray attenuation and visible-near infrared spectroscopy on cores in the field to reduce costs and errors associated with transport, handling, oven-drying, and laboratory measurements (Lobsey and Rossel, 2016). Considering field study results discussed above, any approach taken will ideally need to be capable of characterizing bulk density in deeper soils (> 30 cm in depth) for tracking soil carbon stock changes. Combining traditional field/lab methods (including sample compositing schemes to reduce cost) with emerging spectral methods could help expand the areal extent of monitoring feasible at reasonable cost and should be explored further (Smith et al., 2020; Slessarev et al., 2021).

Another approach that can be employed in the tracking of soil organic carbon is modeling. Many models exist that estimate soil organic carbon dynamics; however, calibration and validation of such models is difficult and not all relevant biogeochemical processes are represented (Smith et al., 2020 and citations within). Some existing modeling tools, such as the Cool Farm tool and the COMET-Farm tool, have existing platforms that can be used to estimate net GHG emissions changes based on farm practices (Cool Farm Alliance, 2019; NREL, 2019). We recommend that the use of models be explored in Vermont as a means of increasing the spatial extent for which soil organic carbon accounting can take place, with one essential caveat: ***models must be properly calibrated using local data to establish confidence in the model results provided***. This inevitably requires field and lab measurements to establish acceptable statistical relationships between modeled and measured values from (a) local benchmark sites undergoing long-term experiments to inform model parameterization, and (b) well-characterized chronosequences or paired sampling sites (Smith et al., 2020). It could be prohibitively expensive to set up benchmark sites covering all possible combinations of land use, climate, soil type, and management practice, so models will likely need to be tested across the full range of parameter space to allow reliable simulation of soil organic carbon (Smith et al., 2020). Without such grounding, models remain unverified abstractions of reality based on untested assumptions, and therefore should not be trusted. This becomes especially concerning in a situation where financial payments or carbon offsets are being determined for climate mitigation services. ***Well-calibrated models, supported by local measurements, could eventually be used to establish relationships between a management change in a particular context (soil, climate, land use, management) and a change in net C fluxes, including estimates of uncertainty, allowing management data reported by farmers to become adequate for reporting and reduce the need for direct measurements (Fitton et al., 2017; Smith et al., 2020). In the views of the authors, this is not yet currently possible in Vermont.***

Additionally, whole systems accounting is needed in order to assess potential trade-offs caused by management strategies and to determine net climate mitigation benefits. Changes in soil carbon stocks are only one piece in climate mitigation accounting: GHG emissions (CO_2, CH_4, N_2O) from soils, livestock, manure management systems, transportation, and farm infrastructure need to be considered as well, as do land requirements and implications for water quality. A narrow focus on soil organic carbon in certain locations could potentially cause net negative consequences for climate and the local environment from a broader perspective. Life cycle assessment (LCA) is an important tool in this context, and useful frameworks exist that can be considered in future Vermont-based efforts using local data (Rowntree et al., 2020; Terlouw et al., 2021).

Stakeholders in Vermont are currently exploring Payment for Ecosystem Services (PES) schemes that could potentially include soil carbon. Based on our assessment of the evidence and literature presented in this chapter, we can answer some important questions that need to be addressed in PES design as follows:

- Are some Vermont farms sequestering carbon from the atmosphere into soils?
    - **YES, this is very likely given the evidence in TNC's AgEvidence and the number of producers using conservation practices in Vermont.**
- Should these farmers be rewarded for their carbon stewardship?
    - **YES, we think some mechanism is needed to reward and incentivize carbon stewardship in agriculture.**
- Can we assume that certain practices will increase permanent C sequestration?
    - **NO, the existing evidence indicates that results will vary for practices based on site-specific factors, and that any carbon sequestered may be reintroduced to the atmosphere due to future management or climatic factors.**
- Is it possible to accurately estimate or model C sequestration without measurements?
    - **NO, models need to be tested against local data to build confidence in their predictions.**
- Should soil carbon sequestration be paid for to offset GHG emissions from other sectors (e.g., fossil fuel use)?
    - **NO, it would be unwise to invest in offsetting the more certain impact of GHG emissions with the uncertain and reversible C sequestration associated with agricultural soil management.**

On the last question, we concur with scholars who suggest that targets and accounting for negative emissions technologies, including agricultural soil carbon sequestration, should be managed separately from existing and future targets for emissions reduction (McLaren et al., 2019). Efforts to balance emissions and offsets within a single accounting scheme to move towards "net-zero" could potentially deter or delay GHG emissions reduction, and therefore negative emissions technologies should be pursued ***in addition to*** rapid emissions reduction (McLaren et al., 2019). A recent report covering protocols for soil carbon sequestration concludes that:

> *"Consistent accounting and verification of direct emission reductions during agricultural production — reduced nitrous oxide emissions via improved nutrient*

> *management, reduced carbon dioxide emissions via reduced tractor use and reduced methane emissions from improved manure management — and from avoided land conversion is a less risky and permanent climate solution [as compared to soil carbon sequestration] for supply chain and other public investment." (Oldfield et al., 2021)*

9.7 RECOMMENDATIONS FOR NEXT STEPS IN VERMONT

Agricultural soil carbon sequestration deserves increased attention in Vermont. However, more research is needed to strengthen the scientific evidence for agricultural soil carbon sequestration in the state, which is currently weak. As mentioned previously, this research could include local benchmark sites undergoing long-term experiments, well-characterized chronosequences or paired sampling sites, and testing the abilities of models to adequately replicate local field and lab data (Smith et al., 2020). Without this research, pursuing carbon offsets or payments associated with soil organic carbon storage on working agricultural lands in Vermont could fail to achieve desired outcomes due to the existing uncertainty concerning climate mitigation benefits, and could in some cases even be counterproductive. Verification of changes in soil organic carbon storage will be critical for any PES program and monitoring can include a combination of direct measurements and models that have been well-calibrated to local agroecosystems. The latter will be necessary for inclusion of GHG fluxes and offsite C impacts, which should be considered in concert with onsite soil organic carbon changes to avoid unintended climate and environmental consequences caused by trade-offs. A challenge will be keeping such monitoring programs cost-effective and manageable. Furthermore, it is important to establish consistent protocols for soil organic carbon estimation and quantification of net GHG emissions reductions in Vermont. Variation in protocols employed would make it difficult to ensure net climate benefits have been achieved and the resulting lack of comparability and standardization would be especially problematic in carbon accounting schemes (Oldfield et al., 2021).

There are several critical knowledge gaps and programmatic questions that need to be answered before launching a large-scale program in Vermont focused on soil carbon sequestration on working agricultural lands (Box 10-1). Equally important is continuing and expanding soil management strategies that maintain existing soil carbon, especially considering the relatively high organic matter levels observed in many Vermont soils.

Box 10-1: Recommendations for research in Vermont to inform future soil carbon sequestration efforts on working agricultural lands in the state, derived from Rumpel et al. (2020) and Amelung et al. (2020).

- Assessment of current soil organic carbon stocks and soil degradation status.
- Assessment of yield gaps and reliable predictions of yield changes with soil organic carbon increases.
- Assessment of soil organic carbon changes by practice and the soil organic carbon storage potential using long-term observations, experimental farm plots, existing state soils data, and appropriate chronosequences.
- Estimation of additional nutrient (N and P) requirements for sustainable C sequestration at the level desired.
- Assessment of the vulnerability of soil organic carbon stocks to determine permanence of carbon storage.
- Selection of methods to account for full life-cycle GHG emissions in farming systems and transfers of organic material that may reduce stored carbon elsewhere.
- Broad ensemble of policies and bottom-up approaches including farmer incentives, standards, and actions to scale up adoption of C sequestering practices.

While the existing evidence for consistent soil organic carbon gains for conservation practices reviewed here is weak, there is more substantial and consistent evidence that many practices recommended for sequestering carbon improve soil aggregation and water infiltration and retention (Dabney, 1998; Jones et al., 1994; Palm et al., 2014). For example, reducing tillage is consistently found to improve soil aggregation (Nunes et al., 2020; Karlen et al., 2019; Mann et al., 2019) which contributes to improved water infiltration and reduced surface runoff. Similarly, cover crops can improve soil water infiltration capacity and aggregation (Magdoff & Van Es, 2009). **Implementing conservation practices as strategies for adapting to climate change and improving farm resilience can likely offer immediate benefits while also providing opportunities to systematically assess the carbon sequestration potential of practices across a range of soil types and farm business models.**

Systematic assessment of carbon sequestration potential on agricultural lands in Vermont will require participatory research conducted in partnership with farmers and land managers. **We advocate for designing future research that builds on the questions, experiences, and observations of producers who are implementing carbon-focused management practices.** Incorporating the complementary expertise of farmers, scientists, and agricultural service providers will be necessary to parse the complex dynamics involved in soil carbon sequestration specifically and the interactions between agricultural soils and a changing climate more broadly. It is important to note, however, that a participatory, long-term approach to soil research may require shifts in the expectations and limitations imposed by current funding mechanisms.

9.8 TRACEABLE ACCOUNTS

Traceable accounts describe the confidence level—the degree of certainty in the scientific evidence—for each key message resulting from this chapter. This analysis is based on the U.S. Global Change Research Program guidance in the Fourth National Climate Assessment (USGCRP, 2018).

<table>
<tr><td colspan="5">Traceable Account 1.</td></tr>
<tr><td colspan="5">Key Message 1: The soil carbon sequestration potential of agricultural management practices in Vermont is uncertain and likely mediated by site-specific factors such as soil type, geography, land use history, and weather.</td></tr>
<tr><td><i>Confidence level</i></td><td><i>Very High</i></td><td><i>High</i></td><td><i>Medium</i></td><td><i>Low</i></td></tr>
<tr><td><i>Description</i></td><td><i>Strong Evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus</i></td><td><i>Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus</i></td><td><i>Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought</i></td><td><i>Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts</i></td></tr>
<tr><td>Finding</td><td></td><td></td><td colspan="2">Low to Medium Confidence that practices will result in soil carbon sequestration. Medium confidence for no till and low confidence for other practices discussed in the main text.</td></tr>
<tr><td>References</td><td></td><td></td><td colspan="2">See main text.</td></tr>
</table>

<table>
<tr><td colspan="5">Traceable Account 2.</td></tr>
<tr><td colspan="5">Key Message 2: Assigning carbon offsets or payments for climate mitigation services provided by Vermont agricultural lands based on practice adoption alone currently lacks a strong scientific foundation.</td></tr>
<tr><td><i>Confidence level</i></td><td><i>Very High</i></td><td><i>High</i></td><td><i>Medium</i></td><td><i>Low</i></td></tr>
<tr><td><i>Description</i></td><td><i>Strong Evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus</i></td><td><i>Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus</i></td><td><i>Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought</i></td><td><i>Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts</i></td></tr>
<tr><td>Finding</td><td></td><td></td><td></td><td>Low Confidence that this approach will yield climate benefits.</td></tr>
<tr><td>References</td><td></td><td></td><td></td><td>See main text.</td></tr>
</table>

Traceable Account 3.				
Key Message 3: Whole-system accounting is required to assess potential trade-offs and to determine net climate change mitigation benefits of soil management strategies.				
Confidence level	*Very High*	*High*	*Medium*	*Low*
Description	*Strong Evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), high consensus*	*Moderate evidence (several courses, some consistency, methods vary, and/or documentation limited, etc.), medium consensus*	*Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought*	*Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts*
Finding	Very High Confidence that this approach is required.			
References	See text.			

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