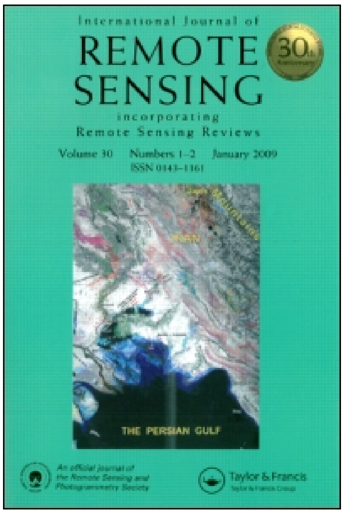

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Vegetation response to ice disturbance and consecutive moisture extremes

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Vegetation response to ice disturbance and consecutive moisture extremes

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Abstract. The resiliency of various components of the natural landscape to stress is a function of the nature and duration of the stress, as well as the individual characteristics of the species of interest. Between 1998 and 1999, four climatic stressors impacted the northern New England region affecting the forest health and agricultural viability of the region. Using multispectral and multitemporal SPOT and Landsat imagery, change vector analysis was performed to separate the effects of the four stressors on the forests, agriculture and water bodies of the Champlain Valley in the state of Vermont. The ice storm of 1998 was found to be a relatively inelastic disturbance, while the precipitation extremes that followed it were more elastic in terms of their impacts on the landscape. A classification scheme was developed to map the spatial extent of the ice storm as a function of observed morphological and physiological variations in the forests.

1. Introduction

The phenology of forested ecosystems and the growth cycle of cultivated crops in a region are adjusted to the climatic elements of that geographic location. Standard levels of physiological functions can therefore be observed under 'normal' conditions. Periodically, one or more of these physiological functions is disrupted by the introduction of stress into the system. These so-called 'stressors' can either be natural or anthropogenic. Examples of the former include variations in site characteristics, abiotic disturbances like fire and severe weather-related events, as well as biotic changes associated with disease and animal intrusions. One of the most evident signs of stress is a reduction in plant vigour. In the case of extreme and/or prolonged stress, complete mortality occurs (Dendron Resource Surveys 1997).

In 1998–1999, northern New England (including Vermont) witnessed four consecutive weather and climate-related events which severely affected the viability of the region's forest health and agricultural potential. The first was a prolonged, widespread icing episode in January 1998, which has been categorized as a 1 in 200 year event (K. F. Jones, US Army Cold Regions Research and Engineering, Laboratory,

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Hanover, New Hampshire, USA, personal communication 2000) damaging 951 000 acres of forest in Vermont alone. This was followed in June and July 1998 by copious rainfall, making that one of the wettest summers on record. By the end of 1998, however, the pendulum had swung in the opposite direction, such that New England and the adjacent Canadian provinces were locked in a drought which lasted through the winter of 1999/2000. Reversal of the drought was initiated in September 1999 by the arrival of two decaying tropical storms/hurricanes within a fortnight of each other.

In examining the influences of the four climatic events, a distinction should be made among stress, strain, disturbance and damage. The ice storm can be considered as a disturbance, whereas the moisture extremes can be thought of as stress. Stress produces physical and chemical changes in plants, the collective effects of which are called strain. In turn, strain can either be elastic, in which case the plant recovers easily and quickly, or it may be inelastic such that plant health and vigour are not recovered. Damage refers to the way in which a plant responds in such a way that sufficient metabolic activity is reserved for repair (Dendron Resource Survey 1997). It should also be noted that only these four climatic stressors were examined over the 2-year period, and other concomitant influences such as forest ageing and urban stress were not specifically addressed.

Given the magnitude and consecutive nature of these four stressors, the main goal of this study was to determine the elasticity of the impacts of the various stressors and to identify the extent to which the causes of these impacts could be distinguished. Focusing on the Lake Champlain Valley in Vermont, the following questions were posed—Could the spatial extent of the ice storm be mapped as a function of the forest response and/or damage? Given the unprecedented magnitude of this ice storm in north-eastern North America over the last 50 years, what was the nature of the recovery under the wetter than normal conditions that ensued? How did plant and, in particular, crop characteristics vary between very wet conditions vis-à-vis drought? Could the elasticity of the response to each of the four stressors be quantified? Apart from the sheer magnitude of the ice storm, one of the reasons for focusing on classifying its effects was that in a state that is 77% forested, an accurate estimate of ice damage in forested ecosystems was crucial in assisting ongoing forest health and productivity decisions made by the Vermont Department of Forests, Parks and Recreation.

In order to address these issues, a number of remotely sensed images were analysed during the pre-events phase (1997), green up in 1998 as well as senescence in 1999. Remotely sensed data have long been recognized as affording valuable contributions to ecosystem response modelling, wetland monitoring and the detection of indicators of physiological changes resulting from stress. The nature of vegetative response to stress is a function of the type and magnitude of the stress (Clevers 1999). Plant water relations under drought stress have been examined by Pinder and McLeod (1999), Duchemin *et al.* (1999) and Calvet (2000). In a separate component of the methodology, a classification scheme was derived to quantify the spatial extent of the ice storm disturbance on forested landscapes only. The challenges faced in simplifying the resulting morphological and physiological variations will be addressed in terms of the hard classifiers used to create the scheme.

A number of measures have been employed to measure stress in plants. These include ratio-based indices (e.g. Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index, Moisture Stress Index), derivatives of the amount of reflectance and the examination of the shifts in the red edge inflection point (REIP).

In this study, change vector analysis (CVA) was used to quantify the magnitude and the type of response in both forested and agricultural systems, as a function of physiological and morphological modifications induced by the external stress. Hydrologic responses were also examined. CVA is usually defined in multispectral space with pixel values being plotted over the time periods of interest. The technique has the advantage of including all the types of change present, allowing the user to differentiate among the various categories of change. In contrast to the multispectral approach, Lambin and Strahler (1994a,b) used a multitemporal methodology to better capture the subtle changes in the seasonality and vegetation phenology of the ecosystems under study. Such frequent temporal sampling is indeed critical for capturing abrupt stressors and long time intervals between phenological events usually introduce the possibility of random weather variations with their corresponding influence on the vegetation response (Linkosalo 2000). However, it can be argued that the stressors to be presented in this study were either very high magnitude (e.g. the ice storm) and/or of extended duration (drought and precipitation excess) such that the effects on the landscape were still very much apparent on the time scale of months, rather than days or weeks. In this study, the Euclidean distance was used to quantify change across the time periods of interest.

2. Study area and climatological context

From 5 to 9 January 1998, a severe icing event impacted much of south-eastern Canada and northern New England, including Vermont. In the most affected regions, ice thicknesses of 76.2 mm were not uncommon causing a variety of damage responses such as broken or bent tree limbs, crown loss or damage and in some cases entire boles, were either split in two or broken below the crown. The ice storm of 1998 was actually composed of a series of icing events which followed through in such rapid succession that little time was allowed for melt and runoff. It displayed the classical vertical structure necessary for a substantial icing event, with a warm layer of air sandwiched between cold air close to the Earth's surface and a second cold layer aloft. At the height of the storm, the freezing layer near the surface was 305–610 m deep (Dupigny-Giroux 2000). As a result, icing damage was located at ground level and again above 427 m, with concentrations of damage above 549 m. Reconnaissance of the ice-damaged forests immediately after the event as well as during the summer of 1998 revealed that the heaviest damage was located on the eastern flanks of the Green Mountains which form a north–south spine along the state (Burns 1999).

Lake Champlain forms a natural boundary between the New England states of Vermont and New York, and landforms in this valley reflect the glacial heritage of the region. The hilly topography is separated from the eastern portion of the state by the Green Mountains. As a result of this isolation, the moderating effects of Lake Champlain are restricted to the lowlands west of the Green Mountains, earning the region the nickname of the 'banana belt'. Here the growing season is longer than in many other parts of Vermont. In January 1998, this relative isolation from the rest of the state allowed cold air to pool largely along the western slopes of the Green Mountains in a cold air damming situation. As a result, ice-related damage tended to be concentrated in this region.

In order to derive an ice damage classification scheme for the Champlain Valley, calibration was performed on a small area, with the results being validated and then applied over the larger region. The study site chosen was the Mount Philo State

Figure 1. Schematic of Vermont's counties with a 1992 colour infrared aerial photograph of the Mt Philo Quadrangle. The study site is indicated with an arrow.

Forest Park (figure 1), located in southern Chittenden County in north-western Vermont. Established in 1924, the 65.2 ha park is the oldest in the state and contained five coniferous plantations (Scots/jack pine (*Pinus sylvestris* L., *Pinus banksiana*), European larch (*Larix decidua P. Mill*), red pine (*Pinus resinosa*), white pine (*Pinus strobus* L.) and Norway spruce (*Picea abies* L.)) which date back to the 1925–1935 period, as well as a variety of northern hardwoods (red oak (*Quercus rubra*), white ash (*Fraxinus americana*), sugar maple (*Acer saccharum*) and beech (*Fagus grandifolia*)). Red oak-white oak and sugar maple-beech stands cover 63% of the park, while Scots and jack pine account for 23% (C. Vile, District Manager, Vermont Department of Forests, Parks & Recreation, Essex Junction, Vermont, USA, personal communication 1999).

Almost every tree on Mt Philo was damaged (Vermont Agency of Natural Resources 1999) and about one-quarter of the park was logged including the red pine plantation. The severity of the ice damage, followed by various stages of forest regeneration made Mt Philo an ideal location for the ice damage classification. Prior to the ice storm, species content and health on Mt Philo had remained virtually undisturbed throughout the 1990s, even though a localized tornado struck the campground on the northern face in 1993. In 1994, the Department of Forests, Parks and Recreation conducted a cruise data study of the western side of the park. This would become the baseline inventory against which the 1998 damage was assessed (C. Vile, personal communication 1999). Finally, the Mt Philo thrust which forms cliffs of at least 213.5 m along the western and southern edges of the park (Dodge 1969) created an altitudinal difference above the surrounding farmland that unequivocally exposed the entire park to ice accumulation during the storm.

Apart from the species present on Mt Philo, Teillon and Wilmot (1991) identify seven forest type groups across Vermont—Northern hardwoods (sugar maple, beech, yellow birch), which account for 61%; white and red pine (14.3%); spruce and fir (14.3%); aspen and birch (4.1%); oak and hickory (3.7%); elm, ash and red maple (2.2%); and oak/pine (0.3%). Many species tend to grow together, increasing the challenge of identifying pure stands at the canopy level. Of these species, American beech and yellow birch sustained more ice-related damage than sugar maples and paper birch. However, sugar maples are the most frequently encountered species in Vermont (Miller-Weeks and Eagar 1999) thereby biasing the perception of extensive damage in their favour. New growth of oak and hickory saplings was observed in areas of complete blow down. As a species, birches were most impacted due to the weakness of the wood. However, given that regeneration is rapid, this species is therefore particularly well suited to this type of disturbance (Lathem 1998).

Following the January ice storm, widespread snow melt and additional precipitation produced several flooding episodes across Vermont by late March/early April 1998. In June and July, a number of severe thunderstorms that moved across the region under the influence of a favourable synoptic weather pattern. It rained almost every day in June. Wet weather continued into September 1998 making that one of the wettest summers on record. This was followed by an abrupt transition into a drought, such that by December 1998, statewide precipitation receipt was only 32% of normal.

The drought of 1998/1999 was initially categorized as mild–moderate, perhaps due in part to the fact that the moisture excess of 1998 helped to dampen any water deficits in soil and vegetation moisture supply. However, by August 1999 the drought severity had intensified to the point that record low flows were observed in both streams and groundwater levels.

On 6–7 September 1999 Hurricane Dennis struck New England. Tropical Storm Floyd followed on 16–17 September bringing statewide totals of 76.2–127 mm of rain. Stream discharge responded rapidly and would have produced flooding and flash flooding had the landscape not been so dry. September 1999 was the second wettest month on record at the Burlington International Airport.

3. Data

Highly resolved spatial and temporal data are needed to adequately biomonitor landscape changes due to ecological damage (Wittich 1997). Given that the ice-related damage left very distinct and significant morphological and physiological responses in its wake, it was imperative to capture corresponding spectral response patterns at the best spatial resolution, over as extensive an areal extent possible.

Five satellite images from three satellites were acquired. Of these, two SPOTView products with a spatial resolution of 20 m were obtained for 7 August 1997 and 14 July 1998. The other three images selected were Thematic Mapper (TM) data from the Landsat series for Path 14, Row 29. The 21 April 1998 image from the Landsat-5 TM sensor was acquired from EOSAT/Space Imaging. From the recently launched (April 1999) Landsat-7 satellite with the Enhanced Thematic Mapper (ETM+) sensor, two scenes were acquired for 21 July and 23 September 1999. SPOTView data have been minimally geometrically and radiometrically corrected, with the application of the State Plane Coordinate (SPC) System for Vermont and the North American Datum 1983 (NAD83) using the GRS80 spheroid. Radiances ($\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}}$) were computed using the gains and offsets included in the respective header files. The Landsat-5 data had a resolution of 25 m and were converted to spectral radiances using the modified gains and offsets of the post 1991 period. Both ETM+ scenes were Level1G processed at the Eros Data Centre (EDC) and involved geometric and radiometric correction to the WGS84 ellipsoid and UTM coordinate system. Absolute radiances were calculated using the LMAX and LMIN parameters included in the Calibration Parameter File. The ETM+ sensor acquires data over the visible (blue, green, red), infrared (near-infrared (NIR), two mid-infrared and two thermal infrared) bands and one broad band panchromatic range. The spatial resolution of these data was 30 m. The TM and ETM+ sensors share common bandwidths with the exception of band 2 (0.52–0.60 μm for TM and 0.53–0.61 μm for ETM+), band 4 (0.76–0.90 μm for TM and 0.78–0.90 μm for ETM+) and band 7 (2.08–2.35 μm for TM and 2.09–2.35 μm for ETM+).

The July/August time frame was selected as the primary period of interest in order to capture spectral responses close to the time of maximum productivity/biomass. Where possible, anniversary dates were selected (7 August 1997, 14 July 1998, 21 July 1999) to minimize non-phenological effects such as sun angle variations. Although the July 1998 SPOTView image contained some high, thin cirriform cloud, it was selected over an August anniversary date due to the much higher cloud cover present on other 1998 summer imagery. The July 1999 TM image was selected to match the 1998 data, while the September 1999 ETM+ images was chosen to coincide with field visits to the study site.

Apart from the main July/August time period, the April 1998 image was also acquired to investigate the green-up in the post ice storm period prior to the mitigating effects of the wet summer of 1998. The May 1998 image would have been more ideal but this was not selected due to a severe line-drop problem. In addition, the September 1999 scene captured harvesting and senescence following prolonged drought in 1998/1999. As aforementioned, the April–September 1998 period in Vermont was particularly rainy, and as such, there were insufficient cloud-free images available to extract senescence/harvesting characteristics in the post ice storm/wet summer period of 1998.

The 1997 image was used as the reference image against which morphological and physiological changes were compared. Phenological variations from the norm, as prompted by fluctuations in moisture inputs and microclimatic influences, were not evaluated. Two reasons for the choice of this date as opposed to an earlier one, involved the antecedent moisture conditions and vegetative health of the forests over the previous two decades. From the early 1980s to 1990, hardwoods in Vermont underwent a period of decline. As recovery progressed the early 1990s, the state experienced a drought in 1994–1995 with a severity reminiscent to those of the mid-1960s. Drought symptoms only become evident over a number of years as was observed by the declines in foliage density in sugar maples in 1995 and 1996. In light of this sequence of decline, drought and recovery, 1997 was an appropriate choice for the reference image.

Apart from satellite imagery, ancillary data on the extent and magnitude of the ice storm damage on the study area (Mt Philo) were obtained from the Vermont Department of Forests, Parks and Recreation (C. Vile, personal communication 1999). These included the aforementioned stand inventory of western Mt Philo performed in 1994, as well as the initial reconnaissance of the ice storm damage of 20 January 1998. Aerial reconnaissance of the entire state in January and late July/August 1998 yielded a GIS-based layer of the areas of damage (see figure 2) as a function of severity (S. Wilmot, Forest Health Specialist, Vermont Department of Forests, Parks & Recreation, Essex Junction, Vermont, USA, personal communication 1999). This layer was instrumental in validating the classification scheme produced in this study. Other supplemental climatological and agricultural information were also used to facilitate the separation of the moisture-related stress. Finally, Digital Orthophotography Quadrangles (DOQs) with a spatial resolution of 0.5 m were acquired for Chittenden County from the Vermont Mapping Program. Flown on 25 April 1999, these greyscale GeoTIFF images represented spring conditions 15 months after the ice storm. (D. Emory, Property Valuation Specialist, Vermont Mapping Program, Property Transfer Data, Vermont Department of Taxes, Waterbury, Vermont, USA, Personal Communication 2000.)

4. Methodology

Prior to their conversion to spectral radiances ($\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}}$), the digital numbers (DNs) of each image were examined for the presence of haze. The DNs for various feature types across the Champlain Valley were compared against the corresponding hourly meteorological observation of Sky Condition made at three airports located in the northern half of the state. This value is determined from both ground-based ceilometer readings as well as satellite determinations of cloudiness at about 3660 m. Based on these readings, as well as the low DN values from the darkest object present (Lake Champlain) according to Chavez (1988), no haze corrections were necessary.

Given the varying spatial resolutions of the input data, pre-processing usually includes the coregistration to a common image and the resampling to a common resolution (usually the coarsest resolution present). In this study, however, the native resolutions were preserved because the issue of mixels would have been confounded had resampling taken place. At the native SPOT and Landsat spatial resolutions, stand purity was questionable and using statistics derived from individual pixels would have increased the error introduced into the methodology. Instead, spectral information was extracted by area using spatial coordinates instead of pixel locations. This ensured that the actual area being sensed was the same across the five images, even if the pixel sizes differed by 5 m. This procedure is called reconciling regions of interest by map in the image processing program ENVI. By reconciling the areas of interest instead of pixels, the data fusion used here is at the feature level using statistical tools (Dai and Khorram 1998).

Following the pre-processing phase, the resulting images were used in one of two ways—to classify areas of ice damage and to quantify the vegetative response to compound stressors. Given the consecutive nature of the latter, it is important to note that (a) the impacts of the ice storm alone can only be isolated by using the July 1997 and April 1998 data and (b) the quantification of the drought response in 1999 did not begin from baseline conditions in 1998.

4.1. *Classification of areas of ice damage*

In order to calibrate ice damage-related spectral responses, field verification was essential. Mt Philo was visited in October and November 1999. Using a Garmin III GPS (Global Positioning System receiver), a database containing the spatial coordin-

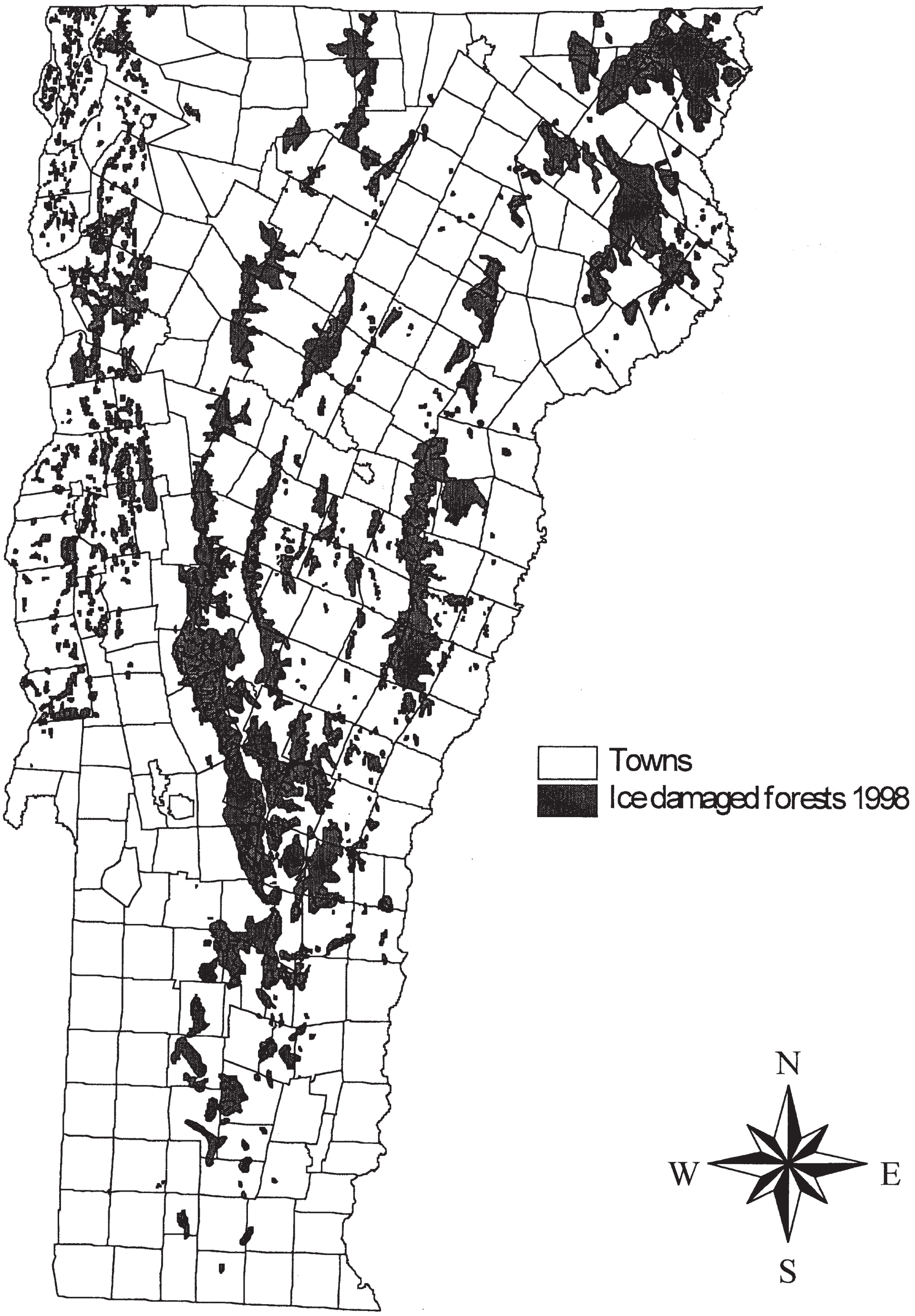


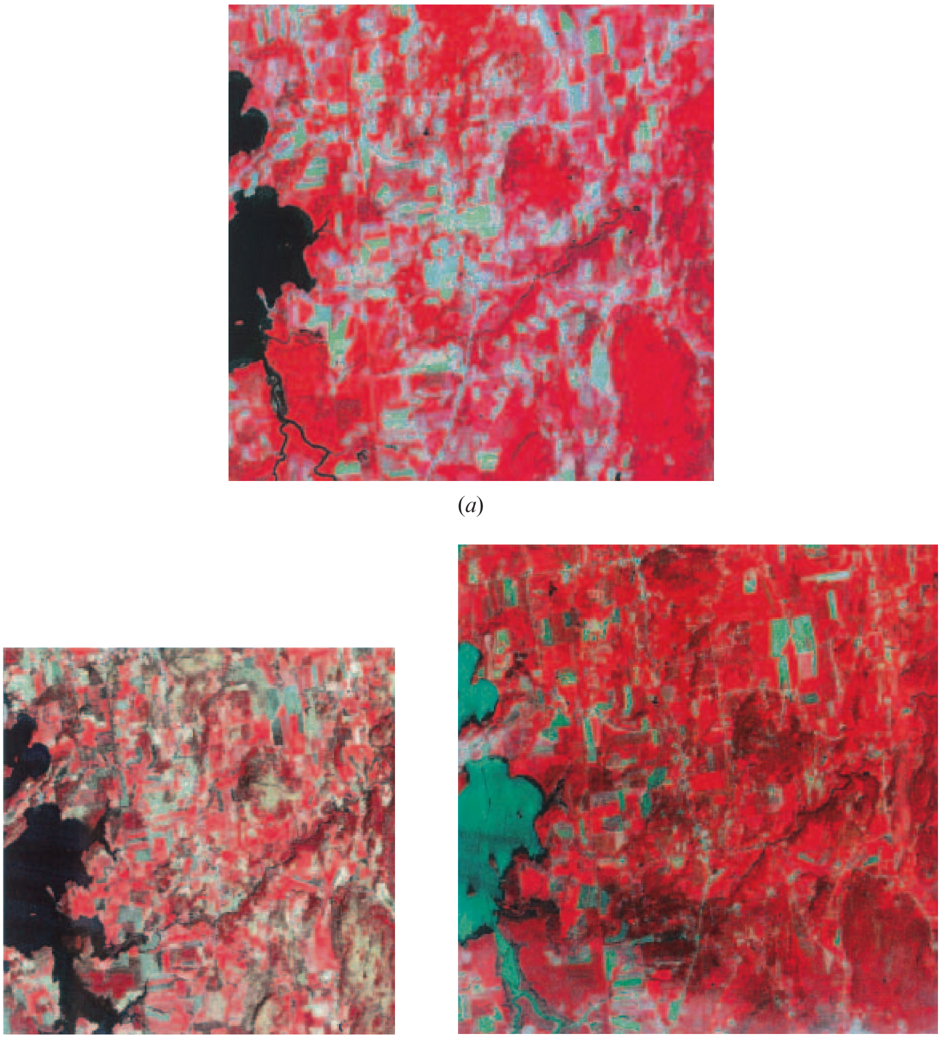
Figure 2. Assessment of damage to forest stands in Vermont due to the January 1998 ice storm. Prepared for the Vermont Department of Forests, Parks and Recreation by Jay Lackey and Tom Simmons.

ates and categorization of tree damage/recovery symptoms present 21 months after the storm, was compiled. Special emphasis was paid to species such as sugar maple, cedar, red oak, paper birch and red spruce/beech/maple combinations given the predominance of these types around the state. These field coordinates were used to query the 1997 and 1998 imagery for the corresponding multispectral radiances. The resulting characteristic response patterns then guided the selection of training sites (called regions of interest or ROIs in ENVI). As aforementioned, given the disparity in the resolutions between the ground data and the satellite information, representative areas were used instead of individual pixels. Initial ROIs included spruce/oak/white pine, oak/maple/beech, sugar maple, paper birch, red pine, Scots pine, logging road and water. A number of hard classifiers (including the Maximum Likelihood classifier, Minimum Distance classifier, Binary Encoding and Parallelepiped classifier) were evaluated for their performance in capturing areas of change. Of these, the Parallelepiped classifier yielded the best results in terms of separating water, urban areas and roads (all grouped together) from forested uplands, riparian vegetation and wetlands.

Three iterations were then performed to produce a layer of ice-damaged areas. In the first iteration, TM imagery from April 1998 was used. Figure 3 shows the colour infrared composites of the study area and its environs for August 1997 (*a*), April 1998 (*b*) and July 1998 (*c*). The most striking observation on the April 1998 imagery is the juxtaposition of the coniferous stands with the largely red oak/beech/sugar maple stands on Mt Philo. Even within these evergreen stands, it was possible to discriminate areas of decreased plant vigour (dull reds, brown) in the Scots pine, while the decreases in vegetation density in the white pine (mauve) in the north-east, were also clearly observed. The deciduous species in their varying pre-leaf-out stages displayed poor plant vigour (green, tan) and in some cases areas of blow down or complete mortality/clear-cutting (blue).

The ice damage classification from the April 1998 imagery produced mixed results for a number of reasons. Overall, ice damage characteristics were best defined for the evergreens, especially in terms of the changes in the amount and vigour of the standing biomass present. For the deciduous species, however, physiological responses were not yet evident because leaf-out had not fully occurred. Even the observed morphological damage (e.g. bent or broken main stems and complete blow downs) was difficult to detect at the canopy level against the background of the broken limbs on the forest floor mixed with the soil response. As such, the April 1998 image effectively yielded a classification of broad species types and not necessarily ice damage extent. This inability to fully grasp or detect the true extent and magnitude of the damage in the weeks and months just after the ice storm, also speaks to tree specialists' caution that 3–5 years would be needed before the real damage could be determined (Burns 1999).

Given the difficulties in separating the ice damage signal from the dormancy and low plant density of the deciduous species in the late winter/early spring period, attention was shifted to the July/August mid-summer time frame, with the aim of detecting ice-related changes in the maximum amount of biomass at the height of the growing season (Jensen 2000). The second and third iterations used SPOT imagery. A comparison between the August 1997 (figure 3(*a*)) and July 1998 (figure 3(*c*)) imagery showed that in the latter time period the amount of standing biomass, level of photosynthetic activity and plant density were much diminished. It was these differences that allowed for a better determination of areas of ice damage



(*a*)

(*b*) (*c*)

Figure 3. Colour infrared extracts of the environs of the Mt Philo study site (including Lake Champlain) for (*a*) 7 August 1997, (*b*) 21 April 1998 and (*c*) 14 July 1998.

than using the spring imagery alone. Image differencing has long been used as a tool in detecting stress and small changes (e.g. Frei *et al.* 1979, Dale *et al.* 1991 a,b), and is an example of the pre-classification approach to change detection (Metternicht 1999). Using the NIR and red differenced (1997–1998) SPOT images, the Parallelepiped classifier produced an image that was visually correct, but the actual percentages of individual tree species across the entire image were not representative of the species distribution characteristic of the state.

One of the reasons for the poor performance of the training sites in the second iteration was the aforementioned fact that species tend to grow together so that the purity of a stand and therefore its corresponding spectral signatures were very much questionable. This was especially true for the adjacent stands of red pine and white pine. Another compounding factor was that by using the species observed in 1999 to help guide ROI selection one of two problems may have arisen. Firstly, the trees left standing after salvaging may not have reflected the original stand composition viewed on the 1997 imagery. Secondly, the extent of damage to the trees left standing was certainly not of the same order of magnitude as the salvaged species. This discrepancy between species/stand composition in 1998 versus 1999 was also reflected in table 1, which compares the 1999 field-observed damaged species with the stands that were observed to be the most impacted on Mt Philo in the weeks following the ice storm. Thus, the lack of convergence between species observed in 1998 and 1999 was a function of the extensive nature of the salvage operations during the summer of 1998, as well as the non-overlap between the plot locations surveyed in 1998 and the field observations in 1999.

In order to overcome the temporal mismatch/stand purity issue, emphasis was shifted to maximizing species differentiation in the pre-storm (1997) as well as post-event period. Covariance-based Principal Component Analysis (PCA) was applied to the 1997 and 1998 SPOT imagery. A correlation matrix would have given each input band equal weighting without taking into account the variability within each image. The first two components (PC1 and PC2) of each period were found to maximize the variance in the data and were therefore instrumental in the selection of new ROIs in the second iteration.

The new training sites were derived from the spectral signatures in the NIR in 1997 and 1998, as well as the 1997 CIR (colour infrared) and RGB composite of PC123 for 1997. These new ROIs were characterized by lower standard deviations (i.e. purer representations of the feature type) and non-essential training sites (e.g. open pasture and water) were omitted. The new training sites included mullein, Scots pine, white pine/Norway spruce, white pine, sugar maple, paper birch, red oak/beech/sugar maple, ash/basswood/other, red pine and white pine salvage areas. The use of a region called mullein (*Verbascum thapsus* L.) refers to regions that were formerly a sugar maple/red oak/beech/paper birch mixture, which had undergone salvage cutting in 1998 and by 1999 were areas dominated by infestations of this woolly plant. The significance of this species will become more apparent in §5.

Table 1. Comparison between the damaged species observed in January 1998 and September/October 1999.

Initial reconnaissance	Field observations
Red pine (*Pinus resinosa*)	Red pine (*Pinus resinosa*)
Scotch and Jack pine (*Pinus sylvestris* L., *Pinus banksiana*)	Paper birch (*Betula papyrifera*)
Sugar maple (*Acer saccharum*)	Sugar maple (*Acer saccharum*)
Norway spruce (*Picea abies* L.)	American basswood (*Tilia americana*)
Hickory (*Carya Nutt.*)	Shagbark hickory (*Carya ovata*)
Red oak (*Querus rubra* L.)	Eastern hemlock (*Tsuga canadensis*)
Beech (*Fagus* L.)	Common mullein (*Verbascum thapsus*)
Black birch (*Betula lenta*)	White cedar (*Tabebuia heterophylla (DC.) Britt.*)
White pine (*Pinus strobus* L.)	
Hophornbeam (*Ostrya virginiana*) Eastern hophornbeam	

4.2. *Validation of the classification*

One of the more common approaches to model development and verification is to develop a scheme at the finest resolution possible and to apply the calibrated methodology to increasingly coarser spatial scales. In this study, the reverse approach was used. By using remotely sensed data at the 20–30 m resolution, canopy-level ice damage was sensed. When airborne data on the order of 1 m or less are used, morphological injury of individual trees is captured. This includes crown loss, die back, arching or complete blow-down/uprooting of trees. The Digital Orthophotography Quadrangles (DOQs) used for the validation were greyscale and lacked the multispectral information that was necessary to examine the physiological response of the affected vegetation.

The validation of the final classified image involved verifying the areas labelled as damage against known damage. Model validation can be thought of as the confirmation that within its specified domain of applicability, the classification scheme possessed a satisfactory range of accuracy, consistent with the intended application of the scheme (after Schlesinger *et al.* 1979 in Tsang 1991). This represents a hybrid of historical data validation and predictive validation. The former refers the use of a part of the image for calibration and the rest for internal validation, while the latter involves checking the classification's predictions against new images (Tsang 1991).

Six sites were selected—Shaw Mountain, Pease Mountain, Snake Mountain, Mt Fuller and East Woods in Vermont and the Bouquet River floodplain in New York. With the exception of the latter two, the other sites are also forested outcrops with species mixtures similar to those found on Mt Philo. In all cases ice damage was well captured. In addition, the presence of mullein on Shaw Mountain in the town of Benson (Ruesink and Graves 2000) was also well captured.

4.3. *Change vector analysis*

In order to quantify the vegetative and hydrologic response to consecutive stressors, change vector analysis was performed for 12 selected feature types, using the overlapping bands (green, red and NIR) of the three sensors, for each of the five sub-periods (August 1997–April 1998, August 1997–July 1998, April 1998–July 1998, July 1998–July 1999, July 1999–September 1999). The total change vector magnitudes (CVM) was computed by the Euclidean distance between the feature values for each of the five intervals.

$$\mathrm{CVM}=\sqrt{\Sigma(X_2-X_1)_i^2} \tag{1}$$

where X_1 is the feature value at time 1, X_2 is the value at time 2 and i is the band (Michalek *et al.* 1993). Table 2 summarizes the vector lengths per period, while change vector plots were created showing the responses of forested, agricultural and urban landscapes, as well as water bodies over time. Green up (G) in 1998 and senescence/harvesting (S) in 1999 were highlighted, although a change vector threshold was not employed for two reasons. Firstly, the deep water areas that are usually the targets against which change is measured were themselves subject to variations in depth and content. Secondly, the direction of change yielded more insights into the underlying physical processes occurring than did the change vector magnitude alone. Directions of change were given by the eight sector codes which represent a composite of positive or negative change in each band (Jensen 1996). This diagram displays the relative effects of the stressors more graphically than spherical coordin-

Table 2. Change vector magnitudes at the green, red and NIR wavelengths for the five intervals between 1997 and 1999.

Features	August 1997–April 1998	April–July 1998	August 1997–July 1998	July 1998–July 1999	July–September 1999
Corn field	54.9	25.1	29.9	25.0	42.1
Hay field	35.6	16.6	23.2	14.7	36.1
Pasture	45.5	18.3	38.8	8.95	23.5
Urban	47.2	33.3	15.7	43.7	41.8
Conifers	56.4	22.6	33.9	21.9	32.2
Riparian	55.4	24.9	30.9	18.9	27.0
Geobotanical	84.3	17.8	67.3	9.1	44.8
Paper birch	54.0	23.2	29.9	18.3	26.8
Wetland	70.2	49.0	33.7	46.7	34.1
Winooski River	75.6	44.9	32.1	12.8	68.9
Shelburne Pond	33.4	52.8	22.9	72.6	85.4
Lake Champlain	16.1	45.7	30.9	37.3	53.4

ates Also plotted is a change vector of magnitude 100, with the 12 feature types at their respective change vector lengths.

5. Results and discussion

The main results of this study are the spatial representation of the extent of ice damage in the Champlain Valley and the quantification of successive stress on selected vegetation and hydrologic elements. Figure 4 shows the final classified image of ice damage in the Champlain Valley, upon which the polygons derived from the 1998 aerial reconnaissance have been superimposed. The image represents the application of damage syndromes for the ROIs derived from the study site. A damage syndrome can be defined as compilation of *a priori* knowledge, photographic interpretation and image enhancements in order to best describe damage characteristics (Lo 1986). The change vector characteristics of these sites as well as other water bodies and crop types will be presented in §5.2. §5.1 will be devoted to the physiological and/or morphological changes associated with the emergence of the species mullein, which has been found to be a useful bioindicator of ice damage. The performance of the classification scheme relative to the aerial reconnaissance will also be presented.

5.1. *Ice damage classification*

On Mt Philo common mullein (*Verbascum thapsus* L.) was primarily found on the north-facing regions that had been salvaged in 1998 to remove trees had either been blown-down or with at least 75% of their tops broken (C. Vile, personal communication 1999). These mullein-infested areas displayed quite dramatic changes in vegetation response over the 1997–1999 period. The 1997 spectral curve indicates that this region was initially dominated by sugar maples which did not afford a very dense canopy before the ice storm, as determined from the low NDVI values. Given the colonizing nature of common mullein which thrives in harsh conditions such as direct sun, thin soils, windswept locations, growth began quickly in this newly disturbed site. Apart from the increased light reaching the floor, the abundant

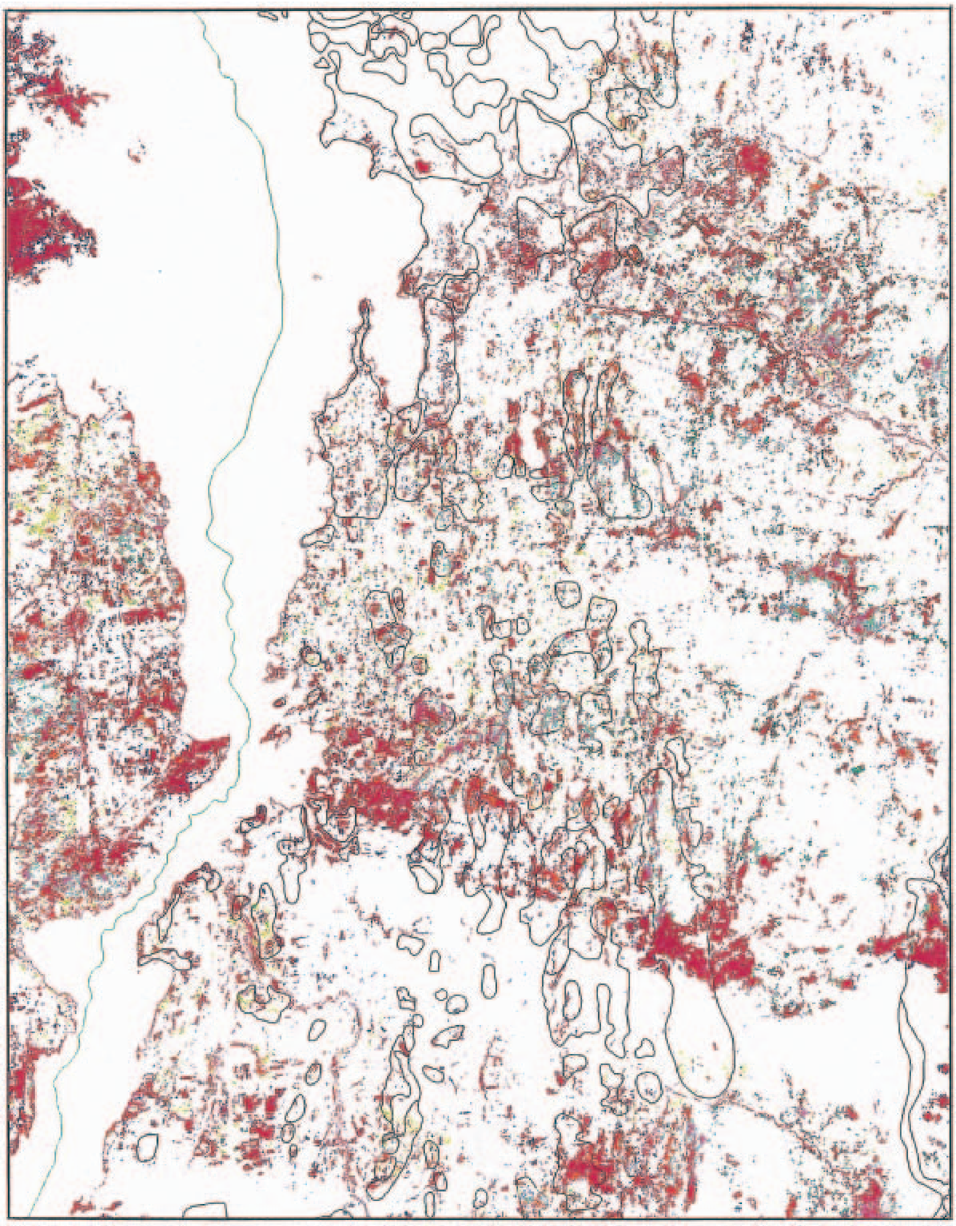


Figure 4. Ice-related damage to forest stands as derived from the July 1998 SPOTView image. The vector polygons shown on figure 2 have been draped over these areas for visual comparison.

moisture present after a wet spring and summer contributed the final factor necessary for the successful establishment and development of this plant (Gross 1980).

Mullein is a biennial that flowers in the summer (late June with a peak in early August) of the second year. During the summer of 1998, these biennials of the *Scrophulariacese* family would have produced a tap root and a rosette of leaves (Hoshovsky 1993). This low-lying, lateral growth would account for both the marked decline in photosynthesis at the red wavelengths as well as decreases in the standing biomass (relative to the predominantly sugar maple stands that were replaced). The relatively dry winter of 1998–1999 was ideal for the overwintering of these mother plants (Lovejoy 1995) so that by July 1999, the plants were at least 180 cm tall and ready to bloom. The latter characteristics were inferred from plant structure and lack of flowers during field visits in October 1999 (figure 5(*b*)). The prolific nature of this biennial would explain the resurgence in photosynthesis observed in 1999 as well as the increase in standing biomass. It is interesting to note that the rapidity of this infestation produced biomass amounts almost on the order of the original sugar maples. The decrease in chloroplast reflection is a function of the phenology of this plant. Gross (1984) measured the growth rate of mullein seedlings on bare versus vegetated soils and found these rates to be four to seven times faster on the former, yielding 2000 times more biomass. The presence of common mullein serves as a bio-indicator of areas of severe damage. Given that mullein is easily out-competed in regions of dense vegetative cover, its presence at similar stages in other parts of the state such as Shaw Mountain in Benson (Ruesink and Graves 2000) and George Brook in the Granville/Ripton area (Faccio 2000) lends strong evidence of ice storm related damage.

The comparison between the classified image and the ice damage map of the Vermont Department of Forests, Parks and Recreation yielded interesting similarities and differences. In terms of similarities, both representations seemed to overlap most in areas of coniferous vegetation. One of the most striking differences was the orientation of the polygons/areas of damage which ran north–south (a function of the flight path), whereas there was no real pattern on the image. Some of the mapped polygons did not coincide with classified areas, with one reason being the inability to locate polygons exactly even on-board an aircraft equipped with GPS capability. Another factor for the lack of coincidence was that some of the classified regions may have been more related to species type rather than ice damage (Trial 2000). The advantage of performing this classification using fairly coarse data (vs aerial reconnaissance close to the ground) was that species like paper birch with their distinctive white barks were easy to locate visually and may have been over represented in any method based solely on visual interpretation. This would apply to either aerial reconnaissance data or large scale aerial photography (e.g. DOQs). In contrast, species such as maples and ash which are single-stemmed may have been overlooked from the air, but not if their spectral characteristics were examined.

Another difference was that riparian areas of damage (e.g. along Otter Creek south of Mt Philo) were not well captured by the original ice map. Conversely, there were several instances (e.g. north of the Greater Burlington area and south of Otter Creek) for which the scheme did not show damage but the ice map did.

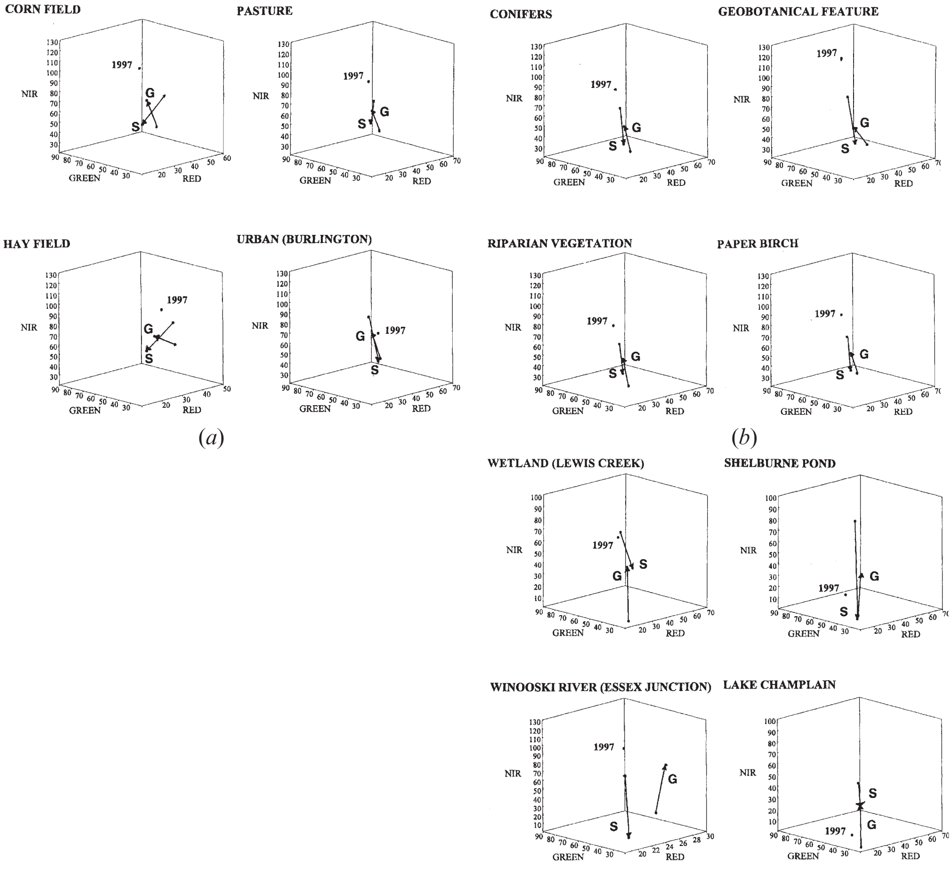
5.2. *CVA results*

For each of the five time periods, the mean value at the green, red and NIR wavelengths was plotted for 12 feature types (figure 6). In terms of the forested areas, both the coniferous and deciduous species were healthiest in 1997. The green-up in 1998 in the post ice storm phase varied in magnitude from minimal in the case of the sugar maple/beech/red oak stands that make up the geobotanical feature along the Mt Philo thrust, through moderate amounts in the case of riparian forests of all types, with maximum amounts in paper birches. This is largely in contrast with the senescence under drought in 1999 which in all cases, was larger than the green-up

(*a*)

(*b*)

Figure 5. Photographs taken in October 1999 on the northern face of Mt. Philo showing (*a*) a stand of sugar maples arched over to the ground and (*b*) the infestation of common mullein.



(*a*) (*b*) (*c*)

Figure 6. Change vector plots for July/August showing the variations in spectral response over the five time periods, and at the red, green and NIR wavelengths for (*a*) agricultural and urban areas, (*b*) evergreen and deciduous vegetation, (*c*) wetland and water bodies. 'G' denotes green-up in 1998 while 'S' refers to senescence in 1999.

the previous year. In addition, the senescence in 1999 occurred along a plane that was shifted to shorter red wavelengths. Thus, although Landsat and SPOT bandwidths are not spectrally well-resolved to detect a shift in the red edge inflection point, the shift in plane towards the blue wavelengths indicates that the response to the drought is not equivalent to that of the ice damage. In using airborne video multispectral imagery to examine sugar maple declines in Ontario, Yuan *et al.* (1991) also found a shift in the red edge reflectance, resulting from changes in crown spectra.

It is interesting to note that, in all cases, although the forested ecosystems' response in July 1999 was higher than in 1998, it was still not at 1997 levels. Two deductions can therefore be made. Firstly, as a disturbance the ice storm was somewhat inelastic, such that full recovery had not been attained within two growing seasons. It should be noted that the wet spring and summer of 1998 were more beneficial in terms of recovery than if a drought had existed. Secondly, the impact of the drought was more elastic than that of the ice storm.

In some respects, the spectral responses among the various crop types paralleled those for forested regions. For example 1997 represented peak growing conditions, while the amount of standing biomass in 1999 the drought year, was higher than 1998 levels. While this may appear counter-intuitive at first, a number of underlying factors may have contributed. Firstly, when freezing rain covers bare agricultural areas, it is first absorbed into the soil and then eventually freezes. As it does so, the air spaces are sealed blocking off the oxygen flow to the lower soil layers. This oxygen deprivation was then observed later in the growing cycle in form of decreased yields. Another factor that could account for the low standing biomass levels was the moisture excess that prevailed in April, June and July 1998. When this is combined with the high clay content found in many soils across Vermont, it is likely that these waterlogged conditions were not conducive to maximum growth. It is interesting to note that although precipitation deficits in 1999 led to the drying of pastures and low hay yields, there was still enough marginal moisture in the early gestation period to allow some crops to sprout, albeit in a more stunted fashion than the conditions observed in 1997. In some cases, the clayey soils which favoured waterlogging in 1998, were able to provide some residual moisture for crop development 1 year later during the drought. In a striking departure from forested regions, agricultural areas showed a shift towards longer red wavelengths in the July time frame. This would imply that the green up under moisture excess produced lower levels of photosynthetic activity than maturity and harvesting during a drought.

As a mixture of hydrophytic vegetation, hydric soils and open water, wetlands represent a transition between riparian forests and water bodies themselves. Here the ecosystem response is related to the physical attributes of the wetland as well as the species composition. Wetlands are an interesting combination of water and vegetative responses and differ markedly from either of these two components. It is interesting to note that unlike the forested regions, July 1999 was the highest in green/red/NIR space. As the driest of the five snap shots, this high NIR value was probably related to the vegetation response as well as the soil background. Wetlands are known for their water retention ability during dry conditions, so that any moisture stress on the vegetation itself may not have been as marked as in a non-hydric forested ecosystem. Another curious observation is the similarity between July 1998 and September 1999 conditions. Both of these high water, leaf-out conditions were probably more related to moisture than a function of the vegetation phenology.

The three water bodies under consideration were Lake Champlain, Shelburne Pond (a smaller inland water body) and the Winooski River at Essex Junction, Vermont before it empties into Lake Champlain. Each represents differences in water depths, ingress/egress, turbidity and the presence of enclosed features. A number of observations are immediately evident. Not surprisingly, July 1999 was the driest period while April 1998 and September 1999 were the wettest. A number of factors contribute to the high NIR values observed during the dry period. The first, which is especially valid for the shallower bodies was the contribution from subsurface volumetric scattering as the water levels declined. In addition, as the drought progressed, blue–green algae began to form on shallow water surfaces as well as inlets along the lake. These organic constituents led to a sharp increase in NIR radiances. On the other hand, the moderately high NIR radiances in July 1998 would have been due to a much different causal factor—that of an increased sediment load as tributaries and other rivers discharged large loads transported downstream due to higher volumes. These higher volumes were in turn a function of the precipitation excess of 1998. The additional reflection and scattering increased the radiant flux back to the sensor (Jensen 2000).

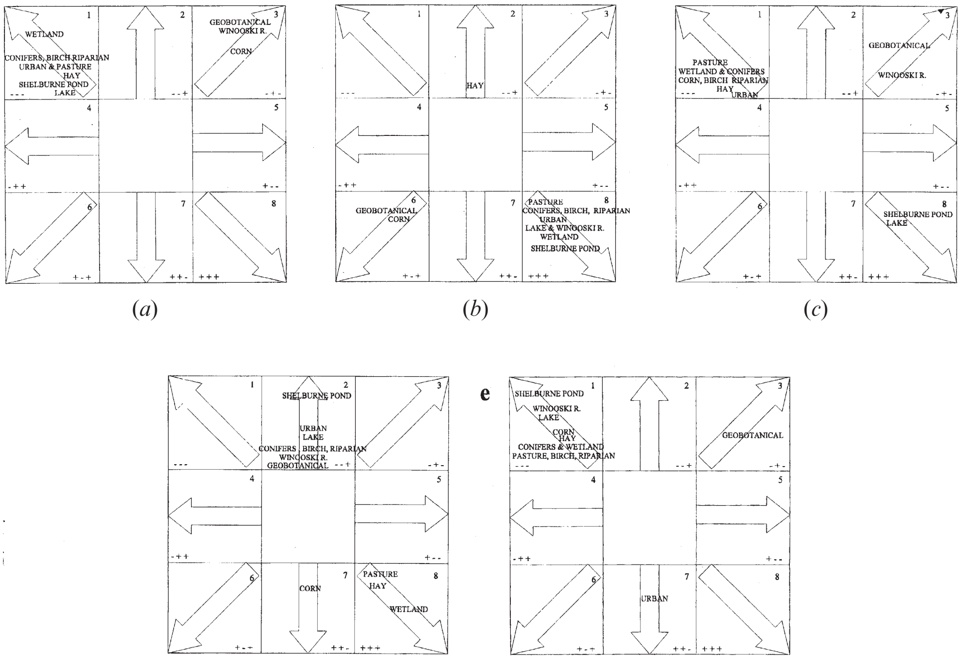
It is interesting to note that the drought signal of 1999 did not occur along the same plane as the moisture excess of the previous year. It is also noteworthy that conditions in 1997 were unlike those of the subsequent 2 years. This could imply that the 1997 snapshot represented clear water, at levels within the bounds for that time of year, and devoid of any influx of sediment or concentrations of organic material.

5.2.1. *Sector codes*

Another way of decomposing the direction and magnitude of the three stressors is via the examination of the sector codes. The change in a given feature type in a particular sector represented very disparate underlying mechanisms for each of the five periods under study. In the following discussion by sector, it is interesting to note that neither sectors 4 nor 5 were observed over the course of the 3 years.

5.2.1.1. *Sector 1*

Change into this sector was observed in the August 1997 to April 1998, August 1997 to July 1998 and July to September 1999 periods. In terms of vegetation, this sector was related to a decrease in standing biomass. The leaf off/dormancy observed in figure 7(*a*) was much larger than that observed during both the drought as well as between 1997 and 1998. In the latter time frame, declines were interposed with morphological changes such as crown loss, limb/mainstem breakage or bending



(*a*) (*b*) (*c*)

(*d*) (*e*)

Figure 7. Change sector codes for (*a*) 7 August 1997–21 April 1998; (*b*) 21 April 1998–14 July 1998; (*c*) 7 August 1997–14 July 1998; (*d*) 14 July 1998–21 July 1999; and (*e*) 21 July 1999–23 September 1999. The magnitude of change for each of the 12 feature types has been proportionally shown, where each arrow represents 100 units.

towards the ground under the weight of the ice (figure 5(*a*)). With decreases in crown loss came the attendant declines in the chloroplast reflection (Jensen 2000). In addition, the decreases in the level of photosynthesis activity were not as dramatic as they otherwise would have been had epicormic branching and sprouting of the understorey not taken place. It should be noted that epicormic branching produces leaves that are not spectrally the same as a full, mature canopy.

Biomass declines were also due to harvesting in 1999. The magnitude of the change vector varied by species, with corn displaying marked differences from pasture and hay.

Hydrologically, a change vector of this direction indicated an increase in water depth and purity. In the August 1997–April 1998 time frame, this was related to the annual peak discharge as snowmelt and spring precipitation combined. In the July–September 1999 period, however, excessive rainfall from the two hurricanes diluted the sediment load and disturbed the algal blooms which skimmed the surface.

5.2.1.2. *Sector 2*

The transition from a wet summer (July 1998) to a dry one (July 1999) was the dominant change observed in Sector 2. All types of forested areas displayed low magnitude vectors into this sector. The overall amount of reflection by chloroplasts declined, while the levels of photosynthetic activity and NIR reflection both increased. One reason for the decline at the green wavelengths is that in the wake of the ice storm and wet summer of 1998, many trees began 1999 with deficient crowns and low root reserves (Burns 1999). As the drought intensified, adaptive tree responses such as the reduction of the surface area for transpiration (observed as leaf scorch and leaf curling) began. It should be noted that the increase in NIR levels indicates that the stress had not developed to the point of causing severe leaf dehydration. The small magnitude change into this sector for the geobotanical feature is surprising given that many of the species (red oak, sugar maple) that comprise it are very susceptible to drought. Again, this would suggest that it is in fact other species (mullein) or levels of maturity (saplings) that were now dominant.

During the same time frame, all of the water bodies were also located in this sector. The fact that both the green and red wavelengths declined is indicative of the lower sediment load in suspension in 1999. However, the presence of blue–green algae produced strong absorption (less reflection) at the red wavelengths and increased surface reflection at the NIR ones. This was particularly evident from the stagnant, enclosed body of Shelburne Pond.

5.2.1.3. *Sector 3*

Change in this direction was dominated by the geobotanical feature and the Winooski River in the August 1997 to April 1998, August 1997 to July 1998 and July–September 1999 time frames. This would imply that ice-related stress observed in the sugar maple/beech/red oak along the Mt Philo thrust differs in magnitude and net result from that observed in either other deciduous species at the study site, or evergreen and riparian vegetation elsewhere. It was along this region that entire stands were salvage cut in 1998 and the windswept nature of the location would set the stage for a mullein infestation later that year.

In terms of the Winooski River, water depths were greater in 1998 compared with 1997, but with these came an increase in suspended loads. The fact that the other water bodies were not observed in this sector implies that the loads may have been urban or agricultural in nature and best detected at the red wavelengths.

5.2.1.4. *Sector 6*

Like Sector 3, the geobotanical feature and corn were observed in the Sector 6 during the green up in 1998. The increased chloroplast reflection, photosynthetic activity and high NIR values indicate a rapid growth rate, much in keeping with the phenological characteristics of mullein. In addition, sugar maples are characterized by slow growth rates and non-existent resprouting ability, whereas red oak saplings are known for their rapid growth spurts once the canopy is opened. Similarly, the growth cycle for corn is also rapid compared with mature forest growth, hence its location in this sector.

5.2.1.5. *Sector 7*

Change into this sector was only observed in corn in the 1998–1999 interval, indicating crop levels of maturity, height and photosynthetic activity that were substantially less in 1999. In fact, a change into this sector indicates vegetative stress, in this case incipient drought conditions that are becoming established.

5.2.1.6. *Sector 8*

The final sector was perhaps the most challenging to quantify. It was dominated by most feature types in the 1998 green up, water bodies in the August 1997–July 1998 interval and crops/wetland in the 1998–1999 time frame. This was not an optimal growth sector for plants since increases at the green and red wavelengths indicated stress due to a lack of chlorophyll pigmentation. Thus, green up in the post ice storm phase was sub-optimal, again reflecting the relative inelasticity of this disturbance.

It is interesting to note that wetland change magnitude and response are essentially equivalent following ice stress as well as in drought conditions. Residual moisture may have accounted the response of the hydrophytic vegetation during the drought. Similarly, low-lying crops were observed in this sector during the same two intervals, indicating their very different response to these stressors than was observed for corn.

Hydrologically, a change into this sector was linked to an increased mineral concentration in suspension, i.e. a transition from relatively pure, deep water to more sediment-laden.

5.3. *Sources of error*

There were four sources of error that need to be accounted for in this methodology. There was a spatial mismatch between the accuracy of the GPS points and the corresponding pixels on the SPOTView or Landsat TM and ETM+ imagery to which they were matched at either a 20 m or 30 m resolution. This inevitably overlapped with the third source of error—mixels. Coniferous plantations tended to be more homogeneous than deciduous stands, although the spectra of the various evergreens were quite similar in some cases (e.g. Scots pine and red pine). Thus, given that there were very few pure stands present at the study site, many of the ROIs used were actually combinations of at least two species.

The time lag among the event (5–9 January 1998), initial reconnaissance (20 January 1998), SPOT image acquisition (14 July 1998) and field visits (October/November 1999) introduced differences in vegetation phenology, species removal, new species (mullein) and perhaps some initial recovery as compounding factors in separating out pre-storm versus post-storm damage.

As aforementioned, the summer of 1998 was particularly wet, making it difficult to acquire completely cloud-free imagery. The SPOTView image from 14 July 1998 showed the presence of high thin cirriform from west to east, south of the study area. This may have affected radiances biasing them to higher values.

6. Conclusions

In attempting to separate and quantify the influence of four atmospheric events on various components of the natural landscape, a number of results can be highlighted. One major outcome of the study was the classification scheme whereby the footprint of the ice storm of 1998 could be traced, following the injury observed in the forested areas. Out of this mapping came the identification of common mullein as a bioindicator of change for areas that had been previously dominated by sugar maples. The emergence of this exotic species as well as the growth spurt of below-canopy seedlings, produced a very different forest regeneration pattern that was observed in both evergreen and other deciduous species. In terms of the timing of capturing the ice damage, monitoring the maximum biomass was found to be more advantageous than early leaf-on imagery.

The ice storm struck after a few years of adequate moisture, such that the vegetation of the area was not under undue stress. Even though the wet summer of 1998 helped to buffer against some of the moisture related stress that could have been detrimental to recovery, the relative inelasticity of this disturbance is evident from the incomplete recovery back to 1997 levels in forests and crops alike. It should be noted that at least 5 years of monitoring are needed to fully quantify the elasticity of this strain. Burns (1999) noted that trees that appeared to be recovering in 1999 may actually decline in subsequent years.

Change vector analysis was found to be a valuable tool for distinguishing among the responses of forests, crops and water bodies to the ice and moisture stressors. Some sectors (e.g. 1 and 8) represented varying stages of phenology and growth stage of plants and crops, with the corresponding vector length indicating the influence of a given stressor. Others reflected the direct influence of the stressor itself, e.g. drought in forests was given by Sector 2, while Sector 7 represented drought in corn. Overall, crops and wetland displayed marked differences to drought than did forested regions.

Finally, a number of lessons can be learned from the timing of the image acquisitions. The first involved the use of data between anniversary dates. For example, the April 1998 imagery was crucial in highlighting the variations in the hydrologic regimes, as well as the initiation of mullein in the study site. On the other hand, the large decreases in NIR reflection that occur in response to loss of plant water and therefore vigour, that usually precedes changes in the visible wavelengths, were not observed by only using anniversary dates at the peak biomass. This inability to monitor such subtle changes was also noted by Lambin and Strahler (1994a) who used a multitemporal (every month in their case) approach rather than a purely multispectral one. An unrelated timing issue revolved around image acquisition immediately after wet weather. As Lillesand and Kiefer (1994) note, stress effects tend to most evident during dry spells, calling into question the exact nature of the responses observed in the April 1998 and September 1999 images.

Future studies are needed in a number of spheres (a) to determine the physiological baseline from which each of these climatic stressors can be measured; (b) separation of the drought signal under non-ice stress conditions; (c) monitoring of senescence patterns in drought versus wet years, but again under non-ice stress conditions; and

(d) ongoing monitoring to determine whether the vegetative reproductive potential has been compromised by the these stressors in the long term.

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