

Subsoil Phosphorus Loss

**A complex problem
with no easy solutions**

by Madeline Fisher

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Andrew Sharpley has studied phosphorus management for three decades now, so there isn't much in the field he hasn't already seen. Take, for example, the University of

Arkansas professor's latest paper in the *Journal of Environmental Quality* (JEQ). In it, he, lead author Douglas Smith of USDA-ARS, and their co-authors reported that half, on average, of all the phosphorus leaving study fields in Indiana did so beneath the ground, through tile drainage pipes. Sometimes belowground losses were as much as 80% of the total. It's considerably more subsurface phosphorus transport than most people might expect, but Sharpley will take exception if you call the finding "new." That's because 30 years ago as a grad student in New Zealand, he was among the first scientists to document phosphorus moving through tile.

The belowground losses he uncovered weren't considered substantial. Like today, though, they were higher than people thought, says Sharpley, an ASA and SSSA Fellow. "So, my feeling is that we have known tiles were a [phosphorus] source for a long time." But, he adds, "not everyone listened."

They're beginning to listen now. Despite decades of work to reduce phosphorus loads into Lake Erie, concentrations of dissolved reactive phosphorus—the main fuel for the lake's persistent algal blooms—have been rising and many researchers now suspect phosphorus in tile discharge is partly to blame. In Europe's Baltic Sea, too, mounting outbreaks of nuisance algae, along with new recognition that their growth is phosphorus-limited, has sparked a sweeping effort in Sweden to cut the phosphorus leaching through subsoil.

New Zealand, meanwhile, has been experiencing some of today's greatest drainage losses of phosphorus, thanks to rapid expansion of dairying and the development and draining of marginal lands. In one case, documented by Rich McDowell of AgResearch, a government-owned research institute in New Zealand, the phosphorus load leaching underground reached 62 kilograms per hectare per year—or

89% of the phosphorus fertilizer applied to the field. That's possibly a "world record," McDowell quips, and it brings home the global nature of the problem.

"Many of us have had this experience now of going around the world and seeing phosphorus in drainage water popping up as this type of surprise, when really it shouldn't be," says USDA-ARS soil scientist and ASA and SSSA Fellow, Peter Kleinman. So a few years ago, he, Smith, Sharpley, and the rest of the phosphorus research community decided to do something about it. At the Societies' 2013 annual meeting in Tampa, FL, they organized a symposium devoted to subsurface phosphorus movement. The symposium has now generated a special collection of papers in the March–April 2015 issue of JEQ, capturing the current state of the science, including Smith's, Sharpley's, and McDowell's work.

Before that, the last significant review was done in 1998 by University of Delaware professor Tom Sims, Kleinman explains. "So we had the sense that we needed to move things forward again." Still, no one expects the way to be quick or easy.

"Subsurface transport is the weakest link in our assessments of the risk for phosphorus loss. So, we need to bring attention to this deficiency and advance our tools to predict it," Kleinman says. But it's hardly low hanging fruit, he adds. "As we've tackled other problems, it has emerged as one of the most intractable things."

More than Water Erosion Management

Part of what makes it intractable is simply the difficulty of observing things that are happening underground, says Amy Shoher, an ASA and SSSA member at the University of Delaware. That's why she, her grad

student Kathryn Clark, and others are now applying a non-invasive tool, electrical resistivity imaging (ERI), to better understand phosphorus movement through ditch-drained soils. However, it's also true that for many years scientists weren't really attempting to look. The prevailing view has been that phosphorus moves from fields almost exclusively at the surface—principally as sediment-bound phosphorus that gets carried into waterways with eroding topsoil.

This is why many of today's best management practices aim to prevent water erosion, says Smith, an ASA and SSSA member with USDA-ARS in Texas. "What we were taught in introductory soils is that if you control erosion then you also control the sediment." And hence, phosphorus.

That's still a good rule of thumb, he adds. But things are also turning out to be much more complicated. Phosphorus that escapes transport in surface runoff or with erosion doesn't necessarily stick to the soil and stay put. In fine-textured, well-structured soils with lots of macropores, for instance, surface water rich in dissolved and particulate phosphorus can leak into holes or cracks in the soil, enter macropores or other paths of least resistance, and travel from there right into drainage pipes and streams. Scientists suspect this is an important loss pathway in the western Lake Erie Basin. And it definitely occurs in Sweden, says Swedish University of Agricultural Sciences professor, Lars Bergström, where 50% of agricultural soils are tile-drained, including most clay soils.

"As a matter of fact, if you fly over Sweden in March or April at the time of snowmelt, you can see plumes of colloids coming out of the tile drains," says the ASA and SSSA member. "So there are a lot of particles leaving the agricultural fields" via the subsurface.

Well-structured, clay soils aren't the only ones that can facilitate belowground phosphorus transport. At the site in Southland, New Zealand where McDowell measured phosphorus losses of more than 60 kilos per hectare per year, the soils are fragile and organic (peat), with high hydrau-



Researchers in Sweden are collecting lysimeters to be used in leaching studies. Photo courtesy of Lars Bergström.

lic conductivity, and low levels of phosphorus-binding aluminum- and iron-oxides. The combination means that the soil has little capacity to sorb any new phosphorus added as manure or fertilizer—leaving a large pool ready to leach through drainage pipes and into streams with the next rainstorm.

Coarse, sandy soils, in contrast, don't transmit phosphorus as readily as fine-textured soils, because sandy soils contain fewer macropores that can serve as direct conduits to tile. "That's counter-intuitive to a lot of people, because everybody thinks that

a sandy soil is like a sieve," Kleinman says. And, in fact, the entire subject is turning out to be counter-intuitive. Nitrate leaching in tile discharge is something farmers, agronomists, and scientists all understand. But "it's hard to grasp that some bits of phosphorus can bypass all the [soil] sinks that are out there, and also flow out through a tile drain," he says.

When Kleinman says "bits" he means it. The amount of phosphorus in drainage water is often quite small: usually well below 1 ppm in concentration, or 2 kilograms/hectare (2 pounds/acre). That's another reason

why the agricultural community neglected the belowground phosphorus transport for so long. The concentrations seemed negligible, so people didn't think they were a concern.

Small Concentrations, Big Impact

Today the concentrations are generally still low; what's changing is our understanding of their impact. In another study in the JEQ special section, USDA-ARS scientist Kevin King and others examined phosphorus concentrations in tile discharge from farms in the Upper Big Walnut Creek watershed—part of Columbus, OH's water supply. Subsurface losses, they found, amounted to less than 2% of phosphorus fertilizer that farmers in the watershed applied to fields, or, in monetary terms, about \$1 to \$2 per acre. And yet, more than 90% of these same concentrations exceeded 0.03 ppm, the recommended limit for curtailing blooms of toxic and nuisance algae.

"So, from an agronomic standpoint, the farmer is doing great," King says. "But from an environmental standpoint, [the loss] is very significant."

"That's difficult," Kleinman adds. "It's right on the margin of what we're capable of managing."

What's more, management practices that are known to prevent erosion or nitrate leaching can actually promote subsurface phosphorus transport—saddling farmers with very tricky environmental trade-offs. One good example is cover crops, known as catch crops in Sweden. In that country and elsewhere, "catch crops are probably *the* most effective method we have to reduce nitrate leaching," Bergström says. But in experiments by his group on catch crops and belowground phosphorus movement, the outcome "has not been positive. It has been the opposite." The problem is that in winter and early spring, cover crop plants repeatedly freeze and thaw, causing their cells to lyse and release dissolved reactive phosphorus. This, in turn, creates a

New Zealand Researchers Develop Inventive Low-P Farming System

Managed pastures are often sown as mixed swards of a grass and a legume, but in New Zealand, there's a movement afoot to separate the two. Planting adjacent monocultures of each crop is already known to boost the quality of livestock forage. Now the thought is it could improve environmental quality, too.

The goal is to stem phosphorus pollution from some of New Zealand's newest pasturelands. Sheep used to be the mainstay of the country's agricultural economy, but today's cash cow is literally that—the cow. During the last 20 years, New Zealand's dairy herd has doubled in size to 6.5 million animals, nearly all of which graze forage year-round, explains Rich McDowell of Lincoln University and AgResearch, a commercial research institute owned by the New Zealand government. As a result, farms have increased in size and expanded onto lands that were once grazed by sheep, but are considered only marginal for dairying.

What makes them marginal are their location—in cool areas of rolling topography at high elevation—and their soils, which have poor structure and are easily compacted by the hooves of cows. These soils are also wet in winter, so “clearly to make them productive, folks have installed mole-pipe [tile] drains to drain what were ephemeral streams,” McDowell says.

Increased compaction can cause phosphorus fertilizer and manure to run off the surface, while the mole-pipes provide a subsurface pathway for phosphorus to travel directly into sensitive downstream waterways. To curb both types of losses, McDowell and his co-authors have now developed an inventive low-phosphorus farming system.

The system described in the Nov.-Dec. 2014 issue of the *Journal of Environmental Quality* has two key pieces. Tillage is performed next to stream banks only, followed by the sowing of two monocultures: ryegrass—a low phosphorus-requiring crop—alongside the stream and clover—which needs more phosphorus fertilizer—upslope of the ryegrass.

What tillage does, first off, is distribute phosphorus-enriched soil at the surface throughout the entire plow layer of soil, lowering phosphorus concentrations there by about half. Tillage can also break up the soil's network of macropores, forcing phosphorus-laden water from the surface to interact with the soil matrix, rather than bypassing it to enter drainage pipes and, hence, the stream.

Plus, any surface runoff moving from high-phosphorus areas of clover will infiltrate into tilled areas that are now lower in the nutrient, thanks again to the redistribution of high-phosphorus topsoil by plowing. In other words, McDowell says, “high P runoff transforms into low P subsurface flow.”

That's the principal mechanism, he continues, and then because “you're planting a species [near the stream], ryegrass, that does well on low phosphorus soil, you're having to put a lot less phosphorus on over time and the soil loses less.” Meanwhile, clover is released from competition with ryegrass, allowing the legume to grow better and producing more high-quality forage.

In short, the practice could be a double victory for profitability and the environment—which is exactly what's needed to inspire adoption. It's a double victory in another way, as well: tackling both surface and belowground losses of phosphorus in one fell swoop.



Split grass clover system in use in one of the experimental watersheds (note the ryegrass around the fenced-off stream and clover elsewhere).
Photo by Rich McDowell.



Photo shows how wet the paddocks can get (the pale green dots are bales of silage produced from the adjacent paddock). *Photo by Rich McDowell.*

new pool of bioavailable phosphorus on the soil surface that can leach downward into the tile system during heavy spring rains.

In short, although cover crops excel at preventing nitrate leaching, erosion, and even particulate phosphorus movement, they don't work for dissolved phosphorus, Kleinman says. "So these are very hard messages to sell. We get into this campaign mode where we want a simple message. But these are not simple problems."

Another dilemma is tillage. No-till and reduced tillage management are being promoted around the world as ways to mitigate soil erosion and improve soil health—which of course they do. However, because reduced tillage enhances the development of soil macropores, it's also suspected of enabling subsurface phosphorus movement.

A related issue is that many no-till farmers still broadcast apply phosphorus fertilizer at the surface, increasing the risk that it will build up there to high levels, leak into preferential flow paths in the soil, and flow into tile drains. This is why on the Ontario, Canada side of Lake Erie—where 75% of farmland is tiled and 30 to 40% of row crop farmers practice reduced tillage—"the go-to way of managing

phosphorus is to band it below the surface, either at or close to planting time," says Keith Reid, and ASA and SSSA member with Agriculture and Agri-Food Canada. The routine is part of a "sufficiency" approach to fertilization, which aims to get a crop response that will pay for fertilizer and maximize net returns in the current year.

The Tri-State Fertilizer Recommendations for Ohio, Michigan, and Indiana, in contrast, follow a "build-up and maintenance" strategy, in which farmers increase soil phosphorus levels to where they no longer limit yields, and then maintain them. "And when all you're doing is maintaining, it doesn't matter how you apply fertilizer," Reid says. Consequently, farmers often opt for the easiest approach: broadcasting. Indeed, 60% of American farmers in the Lake Erie Basin still broadcast phosphorus in the fall, King estimates. "So we've got to get the phosphorus incorporated in some way, even in a no-till framework."

In the meantime, King is experimenting with using minimal tillage to disrupt the macropore network and mix phosphorus-rich surface soils with subsoil. He stresses that he's not advocating a return to all-out tillage. Rather, farmers could till only above drainage lines, for example. Or they might till just one time to "reset" the system in fields where soil test phosphorus values indicate significant stratification. In New Zealand, McDowell is trying something similar: Tilling only next to streams in high phosphorus soils on dairy farms. This is followed by the sowing of a monoculture of low-phosphorus-requiring ryegrass next to the stream and white clover in high phosphorus areas further away (see sidebar).

Although tilling alongside streams defies convention, the approach can reduce leaching of dissolved phosphorus by 44%, McDowell reports, adding that it's practices like this that are needed now. "We have far fewer strategies to cope with subsurface losses [of phosphorus] than surface losses."

Smith agrees. "We hope that more researchers will start looking at phosphorus in tile drainage, both the soluble and total phosphorus forms," he says. "The more minds we can get [working] on the issue, the better off we'll be in finding solutions."

Different Drainage Method, Same Result

On the Delmarva Peninsula adjacent to the Chesapeake Bay, many soils are likewise too wet to farm without drainage, which farmers accomplish in this case with open ditches rather than underground pipes. Yet while the method is different, the result is the same. "On the Delmarva, we have flat topography, so surface runoff and erosion are generally not our two main pathways for phosphorus movement," says the University of Delaware's Shober. Instead, what researchers have detected for years is lateral, subsurface movement of phosphorus through soil into ditch water.

Knowing this is happening, though, doesn't mean the process is understood—far from it, in fact. Delaware's P Index, for example, categorizes *any* ditch-drained field as at high risk for subsurface phosphorus loss, but in reality scientists have a host of questions. Is phosphorus traveling long distances underground before entering a ditch, or are nearby soils the biggest contributor? When during the year is subsurface movement occurring? What soil properties are associated with the largest losses?

As part of a larger project to study and improve the P Index across the entire Chesapeake Bay watershed, Shober is now working with colleagues to get at those questions by tracking water movement—and hence, phosphorus movement—underground. Their method, electrical resistivity imaging, lets scientists peer under the soil surface without disturbing it, and one hope is that the new data will help Delmarva farmers



End-of-tile sampling in Ohio.

assess their true risk for subsurface phosphorus loss.

"The idea that a ditch, is a ditch, is a ditch is not really suitable. Just because a ditch [exists] doesn't mean phosphorus is moving toward it," Shober says. "So, can we identify site characteristics that point us to places where the subsurface is a critical loss pathway? And then how do we target these for some kind of mitigation?"

On another level, though, these kinds of data should help improve modeling of belowground phosphorus movement in general—a neglected area of research that Kleinman believes should be a top priority going forward. "There are currently no fate and transport or watershed models that adequately represent the processes of phosphorus losses to tile drains and drainage ditches," he says. One gap, ironically enough, is that some existing models of drainage losses were developed originally for the Atlantic Coastal Plain (of which the Delmarva Peninsula is a part), where sandy soils predominate. "So they don't work very well for Midwestern soils," says Smith of USDA-ARS. "There's growing evidence to indicate that."

Subsoil properties also need more attention, asserts Bergström. As evidence, he points to recent work by his student Helena Andersson, who examined phosphorus leaching in two sandy soils: One with high topsoil phosphorus levels but a large capacity to sorb the nutrient in the subsoil, and another with less phosphorus in the topsoil and a lower sorption capacity below. The first soil actually lost less phosphorus than the second due to its subsoil properties. But "if you concentrated only on the topsoil, any simulation model you might use in the world would suggest [it would leach more]," Bergström says. "So I'm not saying we should forget about topsoil. But we also have to give some thought to the subsoil."

Much remains to be clarified as well on the impacts of agronomic phosphorus losses on lake ecology;

Interested in this topic? Check out this JEQ special section next month

The *Journal of Environmental Quality* (JEQ) will be publishing a special section of papers on "Phosphorus Fate, Management, and Modeling in Artificially Drained Systems" in its March–April 2015 issue. Look for the articles online mid-March at www.soils.org/publications/jeq (journal subscribers) or <http://dl.sciencesocieties.org/publications/jeq> (Digital Library subscribers).



data from Lake Erie suggest these ecosystems are far more sensitive than people realized and that "it doesn't take much," to trigger a bloom, Sharpley says. Moreover, lakes and bays contain vast stores of "legacy" phosphorus in their sediments that readily diffuses back into the water column. Most of the phosphorus load in the Baltic Sea, for example, is released from the sediments each year, while only a small portion comes from present day agriculture. "So I think we probably need to be doing this work in concert with limnologists," Sharpley says.

At the same time, Sharpley doesn't want researchers to get so focused on the remaining questions that they forget what they already know—especially when it comes to mitigating

the problem. There is ample evidence to suggest, for example, that the sufficiency approach to fertilization already practiced widely in Ontario could do a lot to cut dissolved phosphorus loads into Lake Erie if more farmers adopted it. But the trick will be convincing them that it won't hurt their bottom lines.

"In other words, this doesn't mean we don't need some new research. But we've been doing this a long time, and we *know* what goes on and what will happen," Sharpley says. "So it's finding some way to translate and extend the information that we already have, and demonstrating what can be done—that, I think, is what's important."

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Researchers and technicians from Rutgers, USDA-ARS, and the University of Maryland Eastern Shore set up the electrode array at the field site in Princess Anne, MD. Photo courtesy of Amy Shober.

