Is Vermont Losing Its Oligotrophic Lakes?

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In the early 1970s, a series of experiments conducted in several small lakes in northwestern Ontario established the critical role phosphorus plays in lake ecology. In one of these experiments, now a classic in the history of limnological science, an hourglass-shaped lake was divided into two separate but similar bays using a vinyl curtain installed in the narrow middle section. One bay of the lake was fertilized with nitrogen and carbon, while the other was fertilized with both those nutrients, but in addition, phosphorus. Only the bay fertilized with phosphorus developed algal blooms, turning the bay into pea soup, while the other bay remained clear.

One year after D.W. Schindler published this classic paper on the results of the Ontario experiments (Schindler 1976), the nascent Vermont Lakes and Ponds Management and Protection Program (LPMPP) began monitoring phosphorus. Each year, the LPMPP samples 40-100 lakes and ponds greater than 20 acres (more recently including lakes greater than 10 acres) during spring turnover, following the progression of ice-out from south to north, and from low to high elevation, throughout the state. The goal is to collect water samples for phosphorus testing when the lakes are well mixed, after ice out but before the lakes become stratified by sunshine and warming temperatures. The phosphorus concentrations in these samples give an indication of the availability of phosphorus for the coming growing season and allow us to examine trends in phosphorus concentrations over time. The aim of the program is to visit each lake on an approximately five-year rotation – many lakes have been sampled with even greater frequency.

Lake scientists classify lakes into trophic levels based on the amount of available nutrients in the water that support lake productivity. Nutrients such as phosphorus are necessary to support the growth of algae and aquatic plants. These algae and plants, in turn, support the rest of the lake's inhabitants, including fish, that depend directly or indirectly on these primary producers. Eutrophic lakes have the highest nutrient levels. These lakes support abundant algae and plant growth. Mesotrophic lakes have moderate nutrient enrichment, supporting moderate algae and plant growth. Both eutrophic and mesotrophic lakes support warm water fisheries (e.g., bass, perch, and pickerel). Oligotrophic lakes, in contrast, have low nutrient enrichment. These lakes are clear and deep. They remain well oxygenated to the bottom throughout the summer and they support coldwater fish species (e.g., lake trout, rainbows, and browns)

Although nutrients provide necessary nourishment for the lake ecosystem, nutrients can also become too much of a good thing. Phosphorus becomes a significant pollutant when human activity in a watershed leads to levels that exceed a lake's natural condition. The Clean Water Act facilitated substantial reductions in phosphorus pollution by requiring treatment of waste water and other point sources. However, non-point sources of phosphorus pollution, such as urban and agricultural run-off, remain a concern.

In 2016, Stoddard et al. reported disturbing evidence from the 2007 and 2012 National Lakes Assessments that the total phosphorus (TP) in lakes and ponds has increased on a continental scale. The increases were particularly acute for oligotrophic lakes – those with initial phosphorus levels less than 10 µg/L. Similarly, in updating the Vermont Lake Score Card (http://dec.vermont.gov/watershed/lakes-ponds/data-maps/scorecard) we observed that many oligotrophic lakes in Vermont appeared to be exhibiting increases in TP levels, when examined individually. Prompted by these results, we undertook a more thorough analysis of phosphorus trends in Vermont lakes and ponds over the last four decades.

We examined phosphorus trends in 148 lakes and ponds greater than 20 acres in size that were sampled at least once during the 1980s, at least once since 2000, and have been sampled at least three times with a median of 11 sampling events per lake over 37 years. We defined trophic condition based on the average spring TP for the lake during the 1980s using Vermont's thresholds. The dataset includes 24 oligotrophic (< 7 µg/L TP), 87 mesotrophic (7-15 µg/L TP) and 37 eutrophic lakes (> 15 µg/L TP). The 148 lakes in the study data set aren't a random sample. However, they do not significantly differ from the overall population of Vermont lakes greater than 20 acres with respect to elevation, alkalinity, watershed human disturbance or watershed/lake area ratio (data not shown). Therefore, the study lakes are reasonably representative of all 298 Vermont lakes greater than 20 acres in size.

Figure 1 compares the median and average spring TP concentrations for the study lakes during the decade of the 1980s versus the current decade. The average spring TP for the eutrophic lakes has declined significantly, mesotrophic lakes have increased slightly, while the oligotrophic lakes have increased dramatically relative to their starting point in the 1980s.

We further examined statewide TP trends using a statistical model appropriate for long-term trend analysis. Based on the model, we estimated that eutrophic lakes in Vermont's spring TP dataset have declined in phosphorus, mesotrophic lakes have increased moderately, while oligotrophic lakes have increased dramatically (Figure 2). In fact, oligotrophic lakes on average have nearly doubled in spring TP over the period from 1980-2017, relative to their starting point in the 1980s. Most lakes that would be characterized as oligotrophic in the 1980s now fall into the mesotrophic category, based on spring TP concentrations. We estimated that eight percent of eutrophic lakes have declined, and none has increased in spring TP over the last 37 years, while 38 percent of mesotrophic lakes have increased in spring TP (Figure 3). Alarmingly, nearly 100 percent of oligotrophic study lakes are estimated to have increased in spring TP.

We repeated our analysis using summer data from our Lay Monitoring program – one of the oldest long-term citizen lake monitoring programs in the country. Our volunteers collect an integrated water column sample from twice the Secchi depth, a minimum of eight times over the course of the summer. The sample size for this dataset is smaller, and criteria for inclusion had to be modified. In the data set we analyzed, trophic condition was characterized based on summer TP for all available data prior to 2000. The data include 16 eutrophic lakes, 21 mesotrophic lakes and 4 oligotrophic lakes. The results corroborate what we found using spring TP data. There was no significant change in summer TP for eutrophic lakes, but significant increases in mesotrophic and oligotrophic TP in a large proportion of lakes (Table 1).

Our results parallel those obtained from the National Lakes Assessments reported by Stoddard et al. (2016). Oligotrophic lakes in Vermont showed the most dramatic increases in TP relative to their starting point in the 1980s. In contrast, other researchers have described stable or declining TP in northern hemisphere lakes (Eimers et al. 2009; Huser et al., 2018; Oliver et al. 2017; Jeremy Deeds, Maine DEP, personal communication). Although Oliver et al. (2017) found overall relatively stable

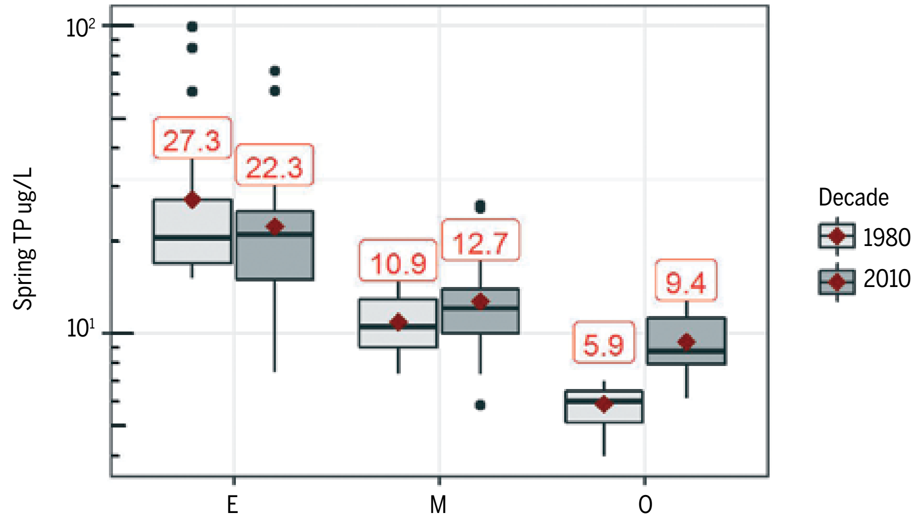

Figure 1. Boxplots (log scale) showing median, first and third quartiles, outliers, and mean (red diamonds and red text) spring TP (µg/L) for eutrophic (E), mesotrophic (M) and oligotrophic (O) lakes during the 1980s (lighter shading) and the current decade (darker shading).

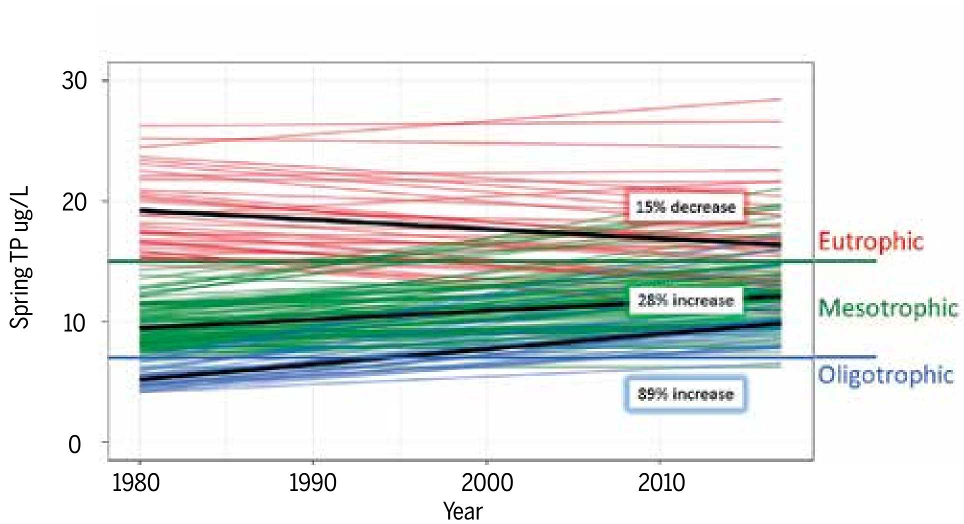

Figure 2. Linear mixed effects model showing the predicted changes in spring TP for individual lakes (solid colored lines, red = eutrophic, green = mesotrophic, blue = oligotrophic), and the overall predicted change in spring TP for each trophic category (solid black lines). Horizontal colored lines represent cut-offs between eutrophic and mesotrophic category (green), and between mesotrophic and oligotrophic category (blue).

Table 1. Percentages of Lakes for Which Spring or Summer TP is Predicted to have Increased, Decreased, or Remained Stable (No Change) Based on the Linear Mixed Effects Model.

	Increased (%)		Decreased (%)		No Change (%)	
Trophic Status	Spring TP	Summer TP	Spring TP	Summer TP	Spring TP	Summer TP
Eutrophic	0	0	8	6	92	94
Mesotrophic	38	90	0	0	62	10
Oligotrophic	100	100	0	0	0	0

TP trends for the northeast U.S., they estimated that 7 percent of lakes and 12 percent of United States Geological Survey (USGS) hydrologic subregions showed increases in TP. Hydrologic subregions are drainage areas that encompass multiple lakes and streams all draining to a single point. One of the hydrologic subregions for which Oliver et al. found a TP increase is USGS subregion

HUC0415, which encompasses more than half of the oligotrophic lakes in our study.

We do not yet know why Vermont's oligotrophic lakes have seen a dramatic increase in phosphorus relative to their starting point in the 1980s. Among the hypotheses Stoddard et al. (2016) considered are climate-related changes (e.g., increased heavy rainfall events), recovery from acid deposition, land use disturbances and phosphorus from dust deposition. Sixteen of 24 oligotrophic lakes in our data set reside in minimally disturbed watersheds, based on a coarse scale Lake Watershed Disturbance Index (Brown and Vivas 2005). However, land use impacts cannot be ruled out as an important source of ongoing phosphorus inputs to Vermont's oligotrophic lakes. Largely forested watersheds may nevertheless exhibit significant development in lake and stream riparian zones that could promote phosphorus run-off. And while Vermont passed a law in 2014 that protects remaining lakeshore buffers, the legacy of unregulated lakeshore development and the lack of riparian buffer protections on the streams that drain into Vermont's lakes are potential sources of phosphorus pollution. Therefore, finer scale characterization of land use patterns in watersheds and riparian areas will be necessary to establish whether non-point TP inputs from the watershed are a significant contributor.

It is interesting to note that phosphorus levels in Maine lakes appear to have remained stable during the same time period as our study (Jeremy Deeds, Maine DEP, personal communication). Maine has had a riparian protection law since 1971 that requires 100' setbacks and vegetated buffers for both lakes and streams draining into lakes.

The good news is that we found no evidence for a general increase in phosphorus across our eutrophic lakes. Perhaps this is at least in part the result of 40 years of clean water act efforts to restore our most polluted lakes and their watersheds. But the increases in TP in Vermont's oligotrophic lakes are cause for great concern. Our long-term monitoring has revealed that Vermont's oligotrophic lakes could be starting down a path to extinction.

Another bit of good news is that lake managers have put a great deal of effort into developing effective methods for reducing and abating the delivery of phosphorus to lakes. The impacts of phosphorus on water quality can readily be addressed at the local level. According to results from the 2007 National Lakes Assessment, Vermont has a larger proportion of oligotrophic lakes than eight of the nine ecoregions in the continental United States and the nation as a whole. The NLA finding that oligotrophic lakes are increasing in TP on a continental scale (Stoddard 2016), combined with our own analysis, suggests we should redouble our efforts to protect our oligotrophic lakes. These low-nutrient, crystal-clear lakes are the jewels of Vermont – especially prized for their natural beauty and recreational opportunities. It would be a shame to lose them.

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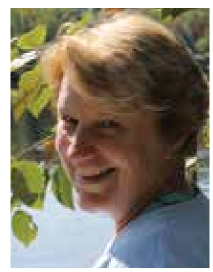

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