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Predicting total phosphorus levels as indicators for shallow lake management

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ABSTRACT

Total phosphorus (TP) is commonly used to assess water quality in shallow lakes and other surface waters. Shallow lakes require special consideration because they can transition between two alternative stable states: (1) a clear-water state that typically supports abundant submerged vegetation and provides high quality wildlife habitat, and (2) a turbid-water state with frequent algal blooms and poor habitat quality. A shallow lake's TP level in relation to critical TP tipping points determines whether the lake is in a highly resilient clear state, a highly resilient turbid state, or whether the lake is in a dynamic region where either state is possible. Further, management options differ for highly resilient clear lakes versus lakes that may be in the turbid state. For example, resilient clear lakes may be assigned special watershed and shoreline protection to preserve their healthy conditions. On the other hand, managers may plan to allocate resources for assessment and possible in-lake management for lakes that have TP levels where the turbid state is possible. Managers would benefit from models that can predict whether a lake is in a resilient clear state or may be in the turbid state without physically visiting a lake to collect water samples or other in-lake data.

We used TP data from 118 shallow lakes in Minnesota and previously estimated TP tipping points to classify lakes as either highly resilient clear lakes ("stable-clear") or possibly turbid ("bistable-turbid"). We used random forest methodology to build models for predicting these two TP classes using both remotely sensed watershed-scale predictors and in-lake variables, and we performed recursive feature elimination to find the most parsimonious model. We demonstrate that TP class can be predicted using only watershed-scale remotely sensed variables and that land cover and use, soil texture, and ecoregion are key predictor variables for TP class. We highlight how our model predictions can be used as indicators to help make management decisions for a set of shallow lakes.

1. Introduction

Shallow lakes are crucial global resources that sustain wetland wildlife, provide critical habitat links between breeding and wintering areas for continental waterfowl, and afford opportunities for outdoor enthusiasts. Shallow lakes generally exist in one of two alternative stable states: a clear state with primary production dominated by submerged aquatic vegetation (SAV) and a turbid state characterized by extreme algal blooms, sparse SAV, and poor habitat quality (Scheffer et al., 1993). SAV and associated epiphyte communities in clear lakes may facilitate the removal of nitrogen (N) from shallow lakes by stimulating coupled nitrification-denitrification processes (Eriksson and Weisner, 1999; Kufel and Kufel, 2002), and parasites associated with amphibian malformations likely have higher prevalence in turbid lakes (Johnson and Chase, 2004). Thus, managing shallow lakes for the clear, SAV-dominated state is important both for wildlife conservation and for removing N from surface waters, which increases local water quality and decreases the export of N downstream.

Theoretical models elucidate how nutrients influence whether lakes tend toward turbid or clear conditions. Fig. 1 is an example bifurcation diagram derived from a model describing shallow lake dynamics (modified from Scheffer et al. (1993)). At low nutrient levels (left of "tip down" threshold in Fig. 1), lakes are attracted to only the clear stable state because the turbid stable state does not exist. Similarly, at high

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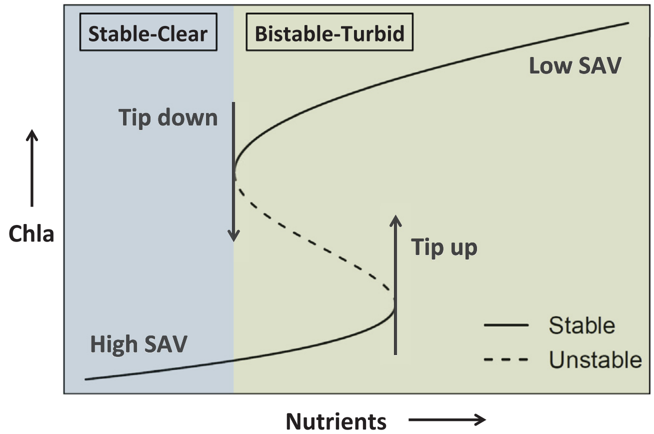

Fig. 1. Bifurcation diagram from a theoretical model describing shallow lake dynamics (modified from Scheffer et al. (1993)). At low nutrient levels (left of "tip down" threshold), only the clear stable state exists (lower solid line). At high nutrient levels (right of the "tip up" threshold), only the turbid stable state exists (upper solid line). In between the two thresholds, the system is bistable, meaning two different stable states are possible under the same nutrient conditions. Lakes with initial chlorophyll *a* (Chla) levels below the dashed unstable line will tend toward the clear stable state, and lakes with Chla levels above the dashed line will tend toward the turbid stable state. In this study, we refer to lakes with nutrient levels below the tip down threshold as "stable-clear" and those that fall above the tip up threshold "bistable-turbid".

nutrient levels (right of the "tip up" threshold in Fig. 1), lakes are attracted only to the turbid state because the clear state does not exist. In between the two tipping points, the system is bistable, meaning two different stable states are possible under the same nutrient conditions. Lakes can switch states either by gradual changes to nutrient levels until a tipping point is reached, or by perturbations that force the system across the unstable line into the basin of attraction of the other state. Shallow lakes are notoriously difficult to restore after shifting from clear to turbid states, with turbid conditions frequently returning within 5–10 years following lake management (Søndergaard et al., 2007). These relapses to turbid conditions suggest that some lakes may fall within the bistable region where perturbations push the system back into the turbid state, or perhaps have nutrient levels beyond the "tip up" threshold in Fig. 1 where only the turbid state exists.

Phosphorus (P) and N have long been known to limit primary production in freshwater lakes (Moss et al., 2013). Recent evidence suggests that local characteristics such as land use and soil types influence which nutrient is limiting for a given lake (Kosten et al., 2009). Nutrient limitation has also been shown to vary seasonally, with shallow lakes being limited by P in the spring and N in later months (Kolzau et al., 2014). Although strong cases have been made for the control of both nutrients in watersheds (Finlay et al., 2013; Moss et al., 2013), management efforts over the last few decades have focused primarily on reducing P loading. These efforts, when successful, have resulted in increased water clarity in shallow lakes (Jeppesen et al., 2007). Thus, we focus here on a model for predicting total phosphorus (TP) levels in shallow lakes as an indicator for management purposes, while acknowledging that a more complete ecological and management narrative may eventually include N.

Previous research has produced estimates for TP tipping points in shallow lakes (Vitense et al., 2018a; Wang et al., 2014; Zimmer et al., 2009). These estimates provide valuable information to managers because a lake's TP level in relation to the tipping points has implications for identifying effective management actions. Clear lakes with TP levels consistently below the lower tipping point are highly resilient, and management efforts for these lakes should typically focus on watershed and shoreline protection. Highly dynamic lakes with TP levels frequently in the bistable region are those for which active in-lake management, such as water level drawdowns or fish removal, is most sensible. Finally, lakes with TP levels beyond the upper tipping point may be lower priority lakes because they will require repeated, intensive interventions to maintain clear water conditions because of the high resilience of the turbid state. Due to the large number of shallow lakes potentially vulnerable to degradation (thousands in the state of Minnesota alone) and the costs associated with collecting and analyzing water samples, managers would benefit from being able to predict lake TP from remotely sensed data. Managers could use these predictions and measures of uncertainty as indicators to prioritize lakes for special protection and to determine the need for additional field data.

Much is known about how watershed features and in-lake biological communities impact nutrient levels and nutrient cycling in lakes. Extensive anthropogenic development, including agriculture and roadways, have contributed to the degradation of many shallow lakes by increasing external nutrient loading, hydrologic connectivity, and drainage from ditches, fields and impermeable surfaces (McCauley et al., 2015; Søndergaard et al., 2007). Increased surface water connectivity has been associated with higher likelihood of fish colonization in shallow lakes (Herwig et al., 2010). Benthivorous fish are particularly problematic in shallow lakes because they disrupt sediments while foraging, keeping nutrients and algae (a major source of particulate P) in circulation (Breukelaar et al., 1994). Benthivores also consume and destroy macrophytes that stabilize sediments (Scheffer, 1998) and translocate P from the lake bottom to the water column through excretion (Andersson et al., 1988).

Geological features of lake watersheds also influence P content in lakes. Soils formed from glacial outwash tend to be well drained, and Minnesota lakes with a higher proportion of glacial outwash in their watersheds have been associated with lower average summer TP levels (Cross and Jacobson, 2013). Plach et al. (2016) showed that a shallow lake on coarse-textured outwash landforms on the Canadian Boreal Plain received groundwater inputs with lower dissolved P and had lower lake TP levels compared to lakes on fine-textured-till hummocky moraine and fine-textured clay-till plains. Shallow lakes in watersheds with finer-textured soils (e.g., clay and silt) may be expected to have higher P content because fine-textured soils can bind more P and are more transportable through watersheds compared to coarse-textured soils (Records et al., 2016).

Here, we use random forest methodology to build models for predicting shallow lake TP levels using both remotely sensed watershed-scale predictors (e.g., land use) and in-lake variables (e.g., fish presence-absence). We use a modified random forest algorithm, RF + +, to account for correlation among within-lake observations, and perform recursive feature elimination (RFE) to find the most parsimonious model in the context of correlated predictors. We demonstrate that TP levels can be predicted using only watershed-scale remotely sensed variables and that land use, soil texture, and ecoregion are key predictor variables for TP. Additionally, we highlight how our model can be used to help make management decisions for individual lakes.

2. Methods

2.1. Data

The Minnesota Department of Natural Resources (MNDNR) sampled 118 lakes once in July during each of three consecutive years, 2009–2011. Six lakes were sampled in only two years, and three lakes were sampled just once. TP was measured in each year, and maximum depth was measured either once (9 lakes) or yearly (109 lakes). Lake maximum depth was determined by measuring depths along parallel transects spaced throughout the open water zone of each site. Water samples for TP were collected at two stations in each lake-year and frozen until analysis with persulfate digestion and ascorbic acid colorimetry. We used average TP values for each lake-year for analysis, and we used TP threshold estimates from Vitense et al. (2018a) to