THE IMPACT OF LAND USE CHANGE ON LAKE PHOSPHORUS CONCENTRATIONS IN DAKOTA COUNTY, MN

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ABSTRACT

In an attempt to improve water quality in the Twin Cities Metro Region in Minnesota, the Minnesota State Legislature passed a law regulating phosphorus (P) in lawn fertilizer. There has been no conclusive study evaluating the effectiveness of the law, due in part to the complex system of sources and transport of P across the landscape that makes it difficult to isolate any one variable. Here we seek to evaluate a single variable, land use, land cover (LULC) change, in order to determine its effect on P concentrations in lakes. Using geographic information systems (GIS), a watershed hydrology model, and spatial metric software, we looked at the relationship between LULC change and lake P concentrations within Dakota County, MN. We found that LULC change had no strong correlation with P concentrations in lakes or between spatial attributes (landscape metrics) of lakes or surrounding land cover and lake P concentrations as well. A simulation of land use change within our study area predicted no significant change in the amount of P in runoff in a ten year period but did predict a significant change in these P runoff when LULC change was extrapolated to 2025. Our results suggest that LULC change may not be a significant confounding variable in evaluating the effectiveness of the Minnesota P fertilizer regulations.

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BACKGROUND AND RATIONALE

In 2005, Minnesota implemented the first state-wide restriction on the application of phosphorus-containing fertilizer on lawns in the United States. The Minnesota Phosphorus Lawn Fertilizer Law aimed to improve water quality and reduce unnecessary P fertilizer use, because excessive concentrations of P in water bodies frequently disrupt ecosystems and decrease the use value of lakes for animals and people (Bennett et al. 2001, Jones and Lee 1982, Smith and Schindler 2009). Severe algal blooms and animal deaths from aquatic toxins have have caused public concern in cases of severe algal blooms and animal deaths from aquatic toxins (Lindon and Heiskary 2007, MPCA 2014). Since then, Maine, Illinois, Wisconsin, Maryland, Michigan, Vermont, New York, New Jersey, Virginia, and Washington have all passed laws similar to the Minnesota law (Miller 2012).

Currently it is unknown how effective these laws are at improving water quality. Minnesota is the logical place to begin studying the effectiveness of the law because it was the first state to pass P lawn fertilizer regulations. Because P levels can fluctuate from year to year, and it takes time for changes in P inputs to result in changes in P concentrations in aquatic systems, it is important to study the effectiveness of P regulations on a landscape where those regulations have been implemented for the longest period of time.

Three years after the law was implemented, Hugoson et al. (2007) attempted to detect changes in P concentrations in Twin Cities watersheds, but were unsuccessful, concluding that the data variability was too high and changes could not be attributed to the law without controlling for multiple confounding variables. Our study investigates one of these confounding variables: land use/land cover (LULC) change. Because land development frequently leads to increased levels of P in runoff and surface waters (Bennett et al. 2001), LULC change may have contributed to raising levels of P in nearby lakes, masking the water quality improvement resulting from the law. We selected Dakota County, MN as our study area due to its high rate of land development from 2001-2011 of all the Twin Cities Metro Region (TCMR) counties.

Research Question:

To what extent does the intensification of land use in Dakota County correlate with total phosphorus (TP) concentration changes in lakes, and is this variable significant enough to account for when evaluating the effectiveness of the Minnesota P fertilizer regulations?

We tested our research question by investigating the following relationships:

A. The relationship between land development and levels of P in runoff.
B. The relationship between land development and TP concentrations in lakes.
C. The spatial attributes of lakes and patches of developed land in relation to the TP levels of those lakes.

We hypothesized that all of these relationships would yield significant positive correlations.

Connection to the 2015 ENTS Comps Theme: Cities in the 21st Century

The proportion of the people living in urban areas has nearly doubled from 1960 to today, currently standing at 54% worldwide. This trend is expected to continue, with an average projected urban growth rate of 1.64% per year through 2030 (WHO 2015). As cities grow to accommodate burgeoning populations, there is increasing research on urban expansion and the conversion of previously undeveloped land affect environmental conditions. Our investigation follows this trend, working in the area of the TCMR that has experienced the most pronounced LULC change in the first 10 years of the 21st Century.

LITERATURE REVIEW

Environmental Impacts of Aquatic Phosphorus

Phosphorus Functions as a Limiting Nutrient in Lakes

Nutrient loading in aquatic environments can alter water quality and aquatic ecosystems. Increases in nutrient concentrations can lead to eutrophication, which involves an increase in net primary productivity (NPP) primarily from algae that subsequently alters ecosystem processes (Alimov and Golubkov 2014). Two nutrients, nitrogen (N) and phosphorus (P), are traditionally studied in the context of eutrophication science. However, P limitation is often more important than N limitation in maintaining lakes in oligotrophic, or non-eutrophic, states (Heiskary and Wilson 2005).

P concentrations are well correlated with abundant algal growth in lakes. In a study of 143 U.S. lakes of varying trophic states, Jones and Bachmann (1976) used July-August TP and chlorophyll *a* (Chl *a*) measurements to examine the relationship between P concentrations and algal growth. They found a strong correlation ($r=0.95$) between the two factors, supporting the hypothesis that P concentrations are linked to algal growth. Additionally, a lake fertilization experiment at the Experimental Lakes Area in Ontario, Canada, Schindler (1977) finds that algal phytoplankton growth in lakes is proportional to aquatic P levels. He hypothesizes that conditions with high TP concentrations favor the presence of N-fixing algae and phytoplankton, possibly ameliorating N limitation symptoms resulting from excess P in the ecosystem over the long term and sustaining primary trends of P limitation.

While P concentrations correlate with algal growth in lakes, understanding their relationship with N concentrations is important in understanding the importance of P in eutrophication processes. In an analysis of mean summer TP and total N (TN) ratios in 221 lakes in 14 countries and associated N limitation experiments, Downing and McCauley (1992) found that eutrophic lakes generally have low TN:TP ratios while oligotrophic lakes have high TN:TP ratios. Nitrogen limitation of algal growth was less common in lakes with high TN:TP ratios and more common when the ratio of TN:TP was low, and low TN:TP only existed when overall TP was high (e.g. when TP exceeded 30 μg/L). The authors conclude that while N and P are capable of acting as co-limiting factors in lakes, N limitation appears to be the norm when $TP:TN < 14$. This suggests that P limitation is more important to maintaining oligotrophic lakes with high TP:TN ratios than N limitation, and thus further supports that P is the primary nutrient capable of promoting eutrophication in lakes.

Restricting N inputs alone is not effective in returning lakes from eutrophic to oligotrophic. Schindler et al. (2008) found that although N had not been applied since 1990, P additions kept the lake eutrophic. Therefore, P loading management should always be considered when addressing nutrient-related water quality issues in freshwater lakes. The authors suggest that unless high N concentrations are harming human health, funds would be better directed towards managing P levels.

Ecosystem Impacts of Eutrophication

Eutrophication and algal blooms from high P concentrations are capable of promoting dissolved oxygen (DO) depletion, fish kills, changes in aquatic macrophyte composition, and the reduction of overall species diversity across aquatic ecosystems (Table 1) (Smith and Schindler 2009). In P-rich eutrophic systems, algal blooms can lead to fish kills by depleting dissolved oxygen resources as they decompose and by introducing toxins to water bodies. As algal organisms die and sink to the lake bottom, the decomposition process deoxygenates deeper water layers. Low oxygen concentrations can facilitate the release of nutrients from lake sediments by encouraging reductive chemical reactions, exacerbating nutrient loading (Cooke et al. 2005). Low DO resulting from eutrophication was the third-most widespread impairment in Minnesota rivers and streams in 2004, ranking below only bacterial contamination and habitat alteration in severity (USEPA 2009).

Oxygen depletion in deep sections of lakes, or the hypolimnetic zone, is positively correlated with mean spring Chl *a* concentrations (Foley et al. 2012). Additionally, the amount of time the hypolimnetic zone spends as anoxic each year rises according to the mean summer Chl *a* concentration. Because Chl *a* concentrations may be used as proxies for algal growth (Jones and Bachmann 1976), it is apparent that DO depletion is linked to the occurrence of eutrophication-related algal blooms.

Fish are susceptible to die-offs and habitat loss when DO levels drop. In an evaluation of water quality and TP concentration trends in Lake Simcoe, Ontario, since 1990, Winter et al. (2007) found that reductions in P inputs were necessary to eliminate excessive plant and algae growth and raise hypolimnetic DO concentrations to acceptable levels for fish survival. The authors recorded minimum end-of-summer DO levels of 4.6 and 4.7 mg/L in 2003 and 2004 respectively, below the 7 mg/L concentration required for the perpetuation of a self-sustaining native trout stock in the lake.

Toxins created by P-induced algal organisms also pose risks to organisms living in lakes, including fish. In 1997, blooms of *Prymnesium* sp. in Lake Vargsundet, Finland, killed an estimated 50% of the fish population, regardless of species, and undetermined numbers of invertebrates (Lindholm et al. 1999). Surviving fish were left with limited habitat after the kill, with *Prymnesium* still occupying surface waters and mid-depth waters containing another toxic algae *Planktothrix* sp., exacerbating restrictions already caused by anoxic conditions in hypolimnic waters.

Microcystins (MCs) are a type of cyanobacteria commonly involved in toxic blooms in eutrophic lakes, and exposure to them can lead to the pooling of blood and cancer in the liver (Belykh et al. 2011). Fish are susceptible to MC algae at concentrations <1 μg/L; during large blooms MC concentrations may reach 25,000 μg/L (OEHHA 2009). In a study of shallow eutrophic lakes in Minnesota, Lindon and Heiskary (2007) found that "severe nuisance" (chl-*a* >30 μg/L) and "very severe nuisance" (chl-*a* >60 μg/L) algal blooms were common throughout the summer of 2006, with lakes exhibiting distinct surface scums having greater likelihood of moderate to high (10-2000 μg/L) MC toxin concentrations.

Eutrophication also leads to changes in large aquatic plant, or macrophyte, abundance and species richness in lakes, with both inversely related to water quality conditions (Egertson et al. 2004; Hilt et al. 2010; Jones and Lee 1982). In a study that used macrophyte surveys since 1896 to investigate the long-term impacts of eutrophication on Clear Lake, Iowa, Egertson et al. (2004) found that species richness declined from a high of 30 species in 1951 to only 12 in 2004. Additionally, the plant community shifted systematically to one dominated by free-floating and emergent macrophytes as eutrophication increased. 93% of the variation in the relative abundance of submerged species at any given time could be predicted by water clarity, with less turbid water yielding higher abundances of submerged species. The authors concluded that species composition shifts were likely linked to the limitation of photosynthesis in at deeper depths as algal blooms made the water less clear.

Impacts of Eutrophication on Human Uses

Algal blooms can reduce the suitability of lakes for human use. The unattractive appearance and odor of blooms may deter users (Smith and Schindler 2009), while toxins pose more tangible threats. MC toxins specifically are of significant concern in Minnesota. Three canine deaths were attributed to elevated MC concentrations in Fish Lake and Lake Benton by the Minnesota Pollution Control Agency (MPCA) in 2004, and anecdotal accounts of bloom-related animal deaths date back to the late 1800s in the city of Waterville (Lindon and Heiskary 2007). Recreational lake users, such as swimmers, water-skiers, and boaters all risk exposure while visiting contaminated lakes and may have symptoms of nausea, skin irritation, and upper respiratory irritation upon water ingestion or contact, although no deaths have been recorded (Lawton and Codd 1991; OEHHA 2009). The MPCA recommends that dog owners keep both themselves and their pets out of and away from waters entirely if they suspect they may be contaminated (MPCA 2014), meaning that even the perceived risk of blooms has potential to render lakes unusable for recreation.

In order to maintain the value of lakes for human use, the MPCA establishes P concentration criteria above which certain uses are considered impaired. In Dakota County, in order for swimming and aesthetic uses be designated as "fully supported," TP concentrations must remain below 40 µg/L. In the southeast portion of the county, partial support for swimming and aesthetics may be maintained until concentrations reach 90 µg/L; no limit for partial support was provided for the northwestern portion (Turner et al. 1998.)

Effects of eutrophication
· Increased biomass of phytoplankton and macrophyte vegetation · Increased biomass of consumer species · Shifts to bloom-forming algal species that might be toxic or inedible* · Increased biomass of benthic and epiphytic algae · Changes in species composition of macrophyte vegetation · Increased incidence of fish kills · Reductions in species diversity · Reductions in harvestable fish and shellfish biomass* · Decreases in water transparency · Taste, odor and drinking water treatment problems* · Oxygen depletion · Decreases in perceived aesthetic value of the water body*

Table 1. Potential effects of cultural eutrophication, caused by excessive inputs of phosphorus and nitrogen to lakes, reservoirs, rivers and coastal oceans. Effects that directly impair human use are marked with an asterisk (*). Modified from Smith and Schindler (2009).

What Contributes to Phosphorus Loading in Lakes?

There is a strong positive relationship between the quantity of P in runoff and P concentrations in surface water (Ann Arbor 2006, Khan and Ansari 2005, Mosley 2015, Waschbusch et al. 1994). P is transported by runoff into surface water in two different forms: soluble and insoluble. Insoluble (particulate) P is usually bonded to soil in permeable land covers and exported in runoff with erosion caused by a large rain event (>2cm, according to Barten et al. 2007). Insoluble P is found in runoff originating from impervious surfaces, and requires a less severe rain event to transport it across the landscape (Heathwaite et al. 2000). Because dissolved P on impervious surfaces requires a less severe rain event to be transported, it is the more common type of P to enter aquatic systems (Sharpley 1995). However, both these dissolved and particulate forms of P ultimately contribute to P loading in water bodies (Fraterrigo 2008).

Impacts of Land Use on Phosphorus Loading

LULC types in a given area influence nutrient loading rates and concentrations in surrounding aquatic systems (Foley et al. 2005, Fraterrigo et al. 2008, Ierodiaconou et al. 2005, Johnes et al. 1996, Soranno et al. 1996). The effect of LULC on nutrient loading is determined by both nutrient availability and the ability of a nutrient to travel through the landscape (Fraterrigo et al. 2008). Anthropogenic inputs can increase nutrient availability, and fertilizer is the top contributor of these inputs (Foley et al. 2005). Other anthropogenic nutrient loading sources include soil erosion, P leaching from pet waste, wastewater, and industrial pollution (Carpenter et al. 1998, Foley et al. 2005).

Vegetation cover, soil type, surface permeability, topography, and climate all influence the ability of a nutrient to travel across a landscape and enter a water system (Johnes et al. 1996). Vegetation cover can reduce nutrient exports, because plant biomass physically blocks the ability of a nutrient to move, and, as P makes up approximately 0.2% of the dry weight of a plant (Schachtman et al. 1998), these plants uptake some of the excess nutrients in the soil (Uusi-Kämppä et al. 2000, Hoffmann et al. 2009, Raty et al. 2010). The amount of P taken up by vegetation depends on both the plant species and P availability (Sachachtman et al. 1998).

Permeability of the land determines the extent to which a nutrient will be absorbed into the ground or transported across the land in runoff (Foley et al. 2005, Fraterrigo et al. 2008, Sorrano et al. 1996). In general, nutrient inputs on less permeable surfaces are more likely to be washed away in the runoff of a rain event (Foley et al. 2005, Fraterrigo et al. 2008). In a model simulation by (Wang et al. 2008), doubling the impervious cover from 30 to 60% increased total runoff by 33%.

Not all nutrients move across a landscape in the same way. Unlike N, which travels through groundwater, P primarily moves in runoff along the surface of a landscape (USGS 1406). Rain events initiate this runoff, which promotes movement of P; Correll et al. (1999) found that precipitation accounted for 42-55% of flux in P exports. While dissolved P is also capable of leaching into deeper soils and moving below ground into water bodies, the quantity of P entering waters by this method is generally small because of its slow speed and the high rate of P absorption by nutrient-poor subsoils (Sharpley 1995). Because of this, accounting for permeability and rain events are necessary when determining LULC impact on P exports (Correll et al. 1999, Fraterrigo 2008, Johnes 1996).

Because LULC impacts nutrient exports, we can infer that changing the LULC of a landscape will result in a change in rate or concentration of these exported nutrients. Changes in permeability, vegetation cover, and anthropogenic inputs in a given area lead to nutrient composition and concentration changes in surrounding aquatic systems within approximately one year of the LULC change (Johnes 1996). This relatively fast cause-and-response time makes the relationship between LULC change and nutrient exports possible to determine.

Spatial Metrics and P Concentrations

The spatial configuration of LULC types can affect the amount of P runoff that enters water bodies (Amiri and Nakane 2009, Wiens 2002, Zhao et. al 2012). Spatial metrics include various measurements of size, shape, fragmentation, and diversity that describe the configuration of landscapes (Calabrese and Fagan, 2004). They can be measured at an individual patch level, class level, or landscape level. Metrics at the patch level examine every connected patch of each LULC type and comparison metrics compare each patch to all other patches. At the class level, metrics examine every LULC type as a single entity regardless of how many patches there are and comparisons are between LULC types or 'classes.' Landscape level metrics look at the landscape as a whole.

A study by Amiri and Nakane (2009) found that 62% of the variation in TP concentrations within streams in their study area could be explained by changes in spatial attributes of land cover in the surrounding landscape. TP levels were positively correlated with higher percentages of urban land cover and LULC change from forest to grassland was correlated with a positive change in TP ($r=0.51$, $p<0.05$). Edge and fragmentation also played an important role in predicting TP concentrations in multiple linear regression models, a result supported by Mayor et al. (2008) which found connectivity of vegetation patches to be a controller of runoff direction and levels.

The findings of Amiri and Nakane (2009) are supported by Wiens (2002), which found that patch boundaries and edges are particularly important in predicting measures of river quality. Related to this, Wiens found that connectivity of patches also plays a key role in river quality measures, concluding that the movement of materials and nutrients in runoff is affected by the spatial configuration of different types of LULC patches. Wiens concluded that scale also plays an important role in determining relationships between land use and nutrient and material movement because relationships that are not apparent at a small scale may be significant at larger scales or vice-versa. These findings suggest that the movement of P in runoff could be largely influenced by the shape, complexity, and distribution of LULC types.

Phosphorus-Containing Fertilizer Regulations

In 2002, the Minnesota State Legislature passed the Minnesota Phosphorus Lawn Fertilizer Law, which restricted the use of P in lawn fertilizers. This law was prompted by three main motivations: improve water quality, clarify confusion caused by multiple local P fertilizer ordinances, and limit extraneous P fertilizer use. When the law went into effect in 2004, the seven counties of the TCMR were prohibited from using P to fertilize lawns unless the lawn was recently sodded, the lawn had been tested and proven to have a P deficiency, or the P fertilizer was applied to a golf course by a trained staff member. The law also mandated that all fertilizer spread or spilled on impervious surfaces, such as roads and sidewalks, must be cleaned immediately. In 2005, these restrictions were expanded to include the entire state of Minnesota. Fertilizer used for agricultural purposes is exempt from these regulations (Hugoson 2007).

Prior to the passing of the law, a study by Barten and Johnson (2007) concluded that there was a 70-80% excess of P present in lawns in the TCMR. Turner and Weddington (1983) show that P in fertilizer only benefits turfgrass growth in its first year, and afterward has no impact on its health in subsequent years. Given that lawns make up 60-70% of urban residential landscapes (Bannermann et al. 1993), and there is an overall excess of P in the TCMR. Policy makers viewed excess P as unnecessary and harmful to the environment, as the extra P is not taken up by plants, but rather remains in the soil or is washed away in runoff, thereby entering aquatic systems, leading to high nutrient concentrations and eutrophication. The State of Minnesota also wanted to use the passing of this law as an opportunity to both educate the public on the impacts of fertilizer use and to make P fertilizer available in stores without creating increased costs to producers or consumers. Currently the largest verifiable impact of the law is the increase in availability and consumption of P-free fertilizers. From 2002 to 2007, the P-free lawn fertilizer availability in the TCMR increased from 5-10% to 97% between 2002 and 2007 (Hugoson 2007).

Although the impact of the law in terms of public awareness and P-free fertilizer availability is clear, its effectiveness in improving water quality is more difficult to determine. The Hugoson et al. (2007) report found that their data was too variable and there were too many confounding factors to draw conclusions regarding the effectiveness of the regulations to reduce P exports. Additionally, lawn fertilizer is not the only source of P in urban environments. Soil erosion, grass clippings, pet waste, and organic matter all contribute to P loading in surface runoff (Hugoson 2007, Fissore et al. 2012). Furthermore, P bonded to lake sediments is released over time, and runoff from agricultural land also enters lakes, making changes in P concentrations in water bodies difficult to attribute to a single source. Despite the multiple confounding variables, several studies have gained insight into the impact of P in fertilizer on water quality.

Barten et al. (2007) conducted the most comprehensive study to date directly addressing the effectiveness of the law. By comparing P exports between pervious and impervious ground in conjunction with rainfall measurements, the author calculated the amount of exports attributed to lawn areas. Rain events < 2cm generated runoff only from impervious surfaces, whereas rain events > 2cm saturated permeable ground (lawns) completely and enabled excess rain to run off from those surfaces as well. Because the study was conducted in locations with different P fertilizer regulation conditions (one with long term restrictions from a pre-existing municipal law and one without) and found significant differences in P exports in rain events > 2cm, but not in rain events < 2cm, it concluded that the P regulations had been effective in reducing P exports from lawns by 12-15%.

In 2007, Ann Arbor implemented a similar ordinance restricting the use of P lawn fertilizer (Ann Arbor 2006). A study by Lehman et al. (2009) measured changes in P runoff in a watershed within the boundaries of the ordinance and in a watershed upstream, which had not been impacted by the restrictions. This study concluded that P levels had declined significantly within the first year. However, while changes in TP begin to become detectable within 1-2 years, the study acknowledges that they may not be able to observe full consequences of the ordinance for up to 8 years for soluble reactive P (Ferris and Lehman 2008). The study concluded that the observed reductions in P were on track to meet the predicted reduction rate of 22% in 8 years. However, as the authors note, it is impossible to fully attribute this reduction to the ordinance, as the law was a part of a larger education effort to inform and encourage residents to implement more P-reducing practices into their yard care, including disposal of yard waste and planting vegetation buffers. Similarly, the Minnesota law was implemented largely through educating the public, and some of the P reductions studied in the TCMR may be in part due to other practices resulting from the regulations.

Nutrient deficient soils may lead to an increase in P exports due to decreased turf quality (Bierman 2010, Easton and Petrovic 2008, Shapiro and Pfannkuch 1973). Bierman (2010) concluded that P runoff for the unfertilized land was significantly greater than for the fertilized land. However, the study also concluded that the turf would be able to maintain adequate health with a P-free fertilizer containing only N and potassium. As long as the lawn was not P deficient, adding P to the system would not impact overall turf quality, and therefore likely not result in increased P exports.

Although these studies indicate that ordinances restricting the application of P lawn fertilizer can effectively reduce P exports, there are still many factors they exclude or fail to separate from others. Most notably, these include LULC change and the impact of public education changing behaviors related to P application and retention in landscapes. As more states and counties adopt these regulations, it becomes increasingly important to gain a greater understanding of the effectiveness of the law and determine what other factors may be important to regulate or include in future studies.

METHODOLOGY

We examined the correlation between LULC change intensity, shape metrics, permeability and P concentrations in lakes and streams within Dakota County, MN. We used geospatial processing software (ArcMap), mathematical modelling software (FRAGSTATS), and land use scenario modeling software (i-Tree Hydro) to examine the relationship between these three variables and P concentrations. When analyzing our results, we used SPSS statistical software designed by IBM to perform statistical tests and graph data. Because this program allows users to examine descriptive and bivariate statistics, perform regressions, and create graphs, we used it to analyze all data present in our results section.

Our analysis takes place between the years 2001 and 2011. We chose the year 2001 because it is the year before the law was passed. Although the law did not go into effect in the TCMR until 2004, many stores and local residents immediately began making the switch to P-free fertilizer in anticipation of the law (Hugoson 2007). We chose 2011 as the end date for our study due to data availability. Spatial data on land use change has not yet been published for recent years.

Study Area

Although the study areas used in our three different analyses have slightly different extents, all of them are based in Dakota County (Figure 1). We chose Dakota County because, according to the National Land Cover Database (NLCD), Dakota County had the highest concentration of urbanization between 2001 and 2011 in the TCMR.

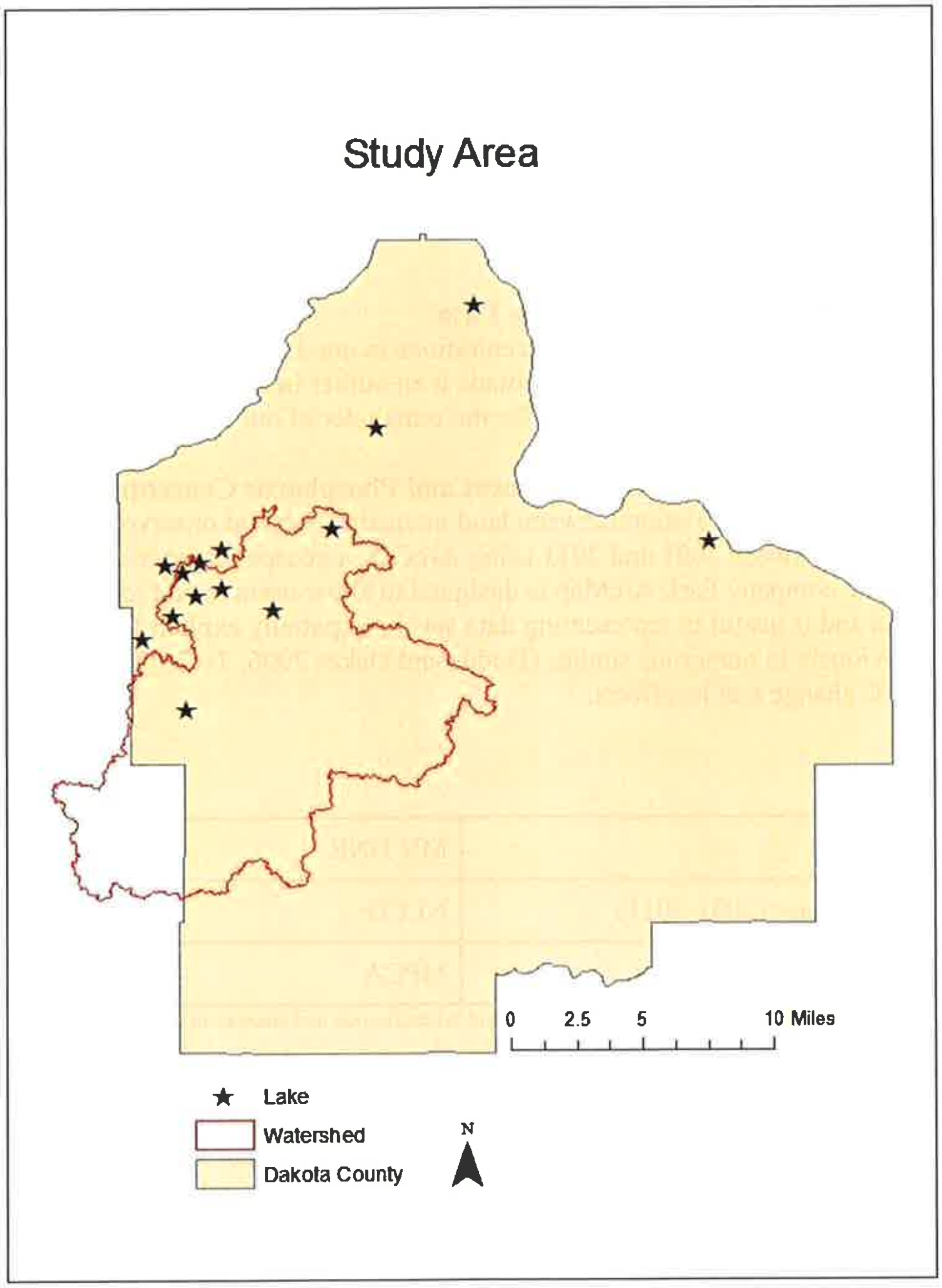

Figure 1. Study areas for our three sub-studies. Each black star represents a lake used in our zonal lake study and shape metric study of developed land. Dakota County marks the extent used for our shape metric study of lakes. The watershed outlined in red marks the extent of the area used by our model, i-Tree Hydro.

Because i-Tree operates on a watershed scale, we were limited to the extent of the 338km^2 watershed with gauge data in Dakota County. Our gauge is located on the Vermillion River near Empire, MN, site number 05345000, coordinates (44.66663318, -93.0549580). For our study comparing LULC change around lakes, we chose our lakes based on data availability for lakes within Dakota County. All of these lakes had both spatial delineations and P concentrations available. There are 13 lakes in our study, reduced from the original 16 we had data for, because two of them had shrunk to a size smaller than our minimum pixel size of 30x30m and one lake had P concentrations that made it an outlier. Dakota County was our study area for our lake shape metric analysis, and for our shape metric analysis of surrounding land cover, we studied a 1k zone around each lake.

Descriptive Statistics on Lake Phosphorus Data

We analyzed the changes in TP concentrations in our 13 lakes between 2001 and 2011. The magnitude of change for Lake Farquar made it an outlier in terms of µg/L change, so we excluded it from our µg/L change analysis for the remainder of our study.

The Relationship between Land Development and Phosphorus Concentrations in Lakes

We assessed the correlation between land intensification and observed average summer TP levels in lakes between 2001 and 2011 using ArcGIS, a geospatial processing program developed by the company Esri. ArcMap is designed to allow users to edit, create, and view geospatial data and is useful in representing data sets in a spatially explicit form. ArcMap has been used previously in numerous studies (Dodds and Oakes 2006, Tu 2011, Zhao et al. 2012) to examine LULC change and its effects.

Data

Lake Delineations	MN DNR
LULC Change Raster (2001-2011)	NLCD
Phosphorus Data	MPCA

Table 2. Data sources used to analyze correlations between land intensification and changes in lake TP levels.

We extracted LULC change proportions extending 30m, 100m, 1k, and 10k around the edge of each of our thirteen lakes in ArcMap. We began with a 30m distance because our LULC change raster has a 30x30m resolution, and we wanted to account for LULC change directly next to the lakes. Our three other distances increase logarithmically starting at 100m. We aggregated the data surrounding the 13 lakes by distance, and then assigned each land cover type a value from 1 to 8, representing the level of anthropogenic intensification (Table 3).

Land Cover	Development Ranking	Description/Ranking Rationale
Deciduous Forest	1	Natural Landscape
Evergreen Forest	1	Natural Landscape
Mixed Forest	1	Natural Landscape
Woody Wetlands	1	Natural Landscape
Grassland/Herbaceous	1	Natural Landscape
Open Water	1	Natural Landscape
Scrub/Shrub	1	Natural Landscape
Barren Land	2	Mostly natural, but can also include gravel pits and mines
Pasture/Hay	3	Includes natural pasture, but also managed hay fields
Cultivated Crops	4	Little natural land, mostly highly managed farming operations
Developed, Open Space	5	Least intense of the developed categories, but includes large impermeable areas
Developed, Low Intensity	6	Low intensity development
Developed, Medium Intensity	7	Medium intensity development
Developed, High Intensity	8	Highest human impact

Table 3. NLCD land cover classes ranked from least to most developed.

After ranking the LULC by level of intensity, we compared the level of intensity of 2001 land cover to 2011 land cover. We found the percentage of pixels for each distance around each lake that increased and decreased in intensity, and the percent change in land cover permeability from 2001 to 2011. We then calculated the net change in P concentrations (μg/L) for each lake and compared them with the net changes in intensity and developed land cover using linear regression analysis in SPSS statistics.

The Relationship between Spatial Configuration and P Concentrations in Lakes

We investigated the relationship between the spatial configuration of pervious cover, impervious cover, and lakes with P concentrations. To do this, we used FRAGSTATS, a spatial mathematical modeling software developed by Oregon State and the University of Massachusetts. FRAGSTATS is public domain software and allows users to examine different landscape metrics and patterns for a particular study area by running pixel by pixel computations on raster data.

Data

We used the same lake delineations, LULC raster, and P data as used for the correlation between LULC change and P lake concentrations (see Table 2), and the watershed extent used in the land permeability analysis (Table 4). We simplified the LULC raster by aggregating LULC types into only three categories: developed, natural, and lakes. Natural included number 1-4 and developed included numbers 4-8 as ranked in Table 3. To keep consistent with our i-Tree Hydro methodology, permeability was used as a proxy for developed land. Because we were concerned only with how the spatial configuration of lakes and developed areas relates to P levels in lakes, aggregating LULC types allowed for relationships to be seen more clearly.

Calculations

We chose to run our analysis at the class level in order to examine the relationship between lakes and different landscape metrics of developed areas as a whole. We examined the following metrics in our analysis: TA/CA (total area), TE (total edge distance), SHAPE (shape complexity), PARA (perimeter-area ratio), and ENN (euclidean nearest neighbor). The first two metrics (CA, TE) were chosen to further investigate our earlier finding that lake size seems to have little relationship with P concentration, suggested metrics by Zhao et al. (2012). SHAPE and PARA were chosen to investigate whether lakes with more complex shapes and perimeter had higher or lower P levels because they could potentially have more area exposed to P runoff than lakes with lower complexity (Amiri and Nakane, 2009). Higher values of SHAPE mean more complexity in the shape of the patch and higher values of PARA (m/ha) mean a larger perimeter in relation to area. ENN was chosen to help us assess the fragmentation of pervious and impervious cover, an important factor in determining runoff into lakes (Wiens 2002). Higher values of ENN at the class level mean larger average distances between a patch of any particular class and the next nearest patch of the same class. After choosing our metrics, we ran the software once for lakes, and once for impervious cover.

The Relationship between Land Permeability and Phosphorus Levels in Rainwater Runoff

The Model

In order to predict the effect changes in land permeability have on P exports, we used the model i-Tree Hydro. I-Tree Hydro was developed at SUNY College of Environmental Science and Forestry for the purpose of giving land managers and policy makers an accessible way to compare the predicted impacts of different land use scenarios. It focuses on two aspects of land use change: land imperviousness and tree cover. Our study uses imperviousness as a proxy for the intensification of land. According to the Endreny (2005), "another definition of intensity is to consider impervious area (Schueler, 1994), proposed by the Water Environmental Federation (WEF) and American Society of Civil Engineers (ASCE), as a single unifying measure of the effect of urbanization on watershed hydrology". By assuming intensifying land use, we can find the estimated impact of land development between 2001 and 2011 on P runoff. I-Tree also makes the assumption that rainfall is proportional to P concentrations in runoff and a study by Zhao et al. (2012) found a close correlation between runoff and rainfall levels (0.867) which supports the assumption in this study and in the i-Tree model that most runoff occurs during rain events and is proportional to rainfall levels during each event.

Data

Input	**Source**
Digital Elevation Model (DEM)	USGS
Weather Data (2006)	i-Tree
Stream Gauge Data (2006)	USGS
Land Cover Ratios	NLCD
Watershed Extent	EPA

Table 4: User inputs to i-Tree Hydro. After downloading the DEM from the USGS, we delineated the streamflow direction using ArcMap. Weather and gauge data are from 2006 because it had the most complete weather station data and had data consistent with surround years, except for 2007, which had an abnormally high amount of precipitation.

I-Tree requires the input of large datasets and spatial layers (Table 4) and user-defined land cover and permeability proportions (Table 5).

Land Cover (%)	**2001**	**2011**	**2025**
Tree Cover	9.9	7.4	3.9
Shrub Cover	1.0	1.0	1.0
Herbaceous Cover	58.0	52.1	43.8
Water Cover	1.0	2.4	4.4
Impervious Cover	30.0	36.8	46.3
Soil Cover	0.1	0.3	0.6

Table 5: Inputs for land cover for i-Tree Hydro for base case (2001) and alternate case (2011), and projected values for 2025. Impervious cover includes NLCD land cover classes Developed, Open Space, Low Intensity, Medium Intensity and High Intensity. Tree cover includes Deciduous Forest, Evergreen Forest, Mixed Forest, and Woody Wetlands. Herbaceous includes Grassland/Herbaceous, Pasture/Hay, and Cultivated Crops. There is likely some error associated with these percentages; they are based on the proportion of 30x30m pixels classified as each LULC type on a LULC raster. Because there are often multiple LULC types within a 30x30m area, there is some variability as to which LULC is determined to be the dominant type.

Simulations

We ran three different land cover scenarios (2001, 2011, and 2025), holding all other variables constant. The 2001 and 2011 land cover proportions represent the actual land cover during those time periods. We used the observed change between 2001 and 2011 to estimate the predicted LULC proportions for 2025. After running each scenario, we were able to compare the predicted P runoff concentrations.

RESULTS

Observed Changes in Land Cover

Between 2001 and 2011, the average cover of developed land in all zones extending from the shores of our study lakes (10000, 1000, 100 and 30m) increased. This measure included cover types develop 5-8 in Table 3. However, the only zone that showed a significant increase at an α level of 0.05 was the 1000m zone (Table 6.)

Zone Extent (m)	Average 2001 Developed Cover (%)	Average 2011 Developed Cover (%)	Average Change in Developed Cover, 2001-2011 (%)	p-value (paired samples t-test)
10000	50.2 (4.0)	53.7 (3.9)	3.5 (1.7)	0.066
1000	81.1 (5.2)	83.4 (5.0)	2.3 (0.9)	0.026*
100	72.0 (7.7)	75.4 (6.4)	2.5 (2.0)	0.243
30	74.3 (4.6)	79.0 (6.0)	4.7 (3.9)	0.255

Table 6. % change in developed land cover within lakeshore zones from 2001 to 2011. Significant changes at an α level of 0.05 are marked with an asterisk (*). Values in parentheses are mean standard errors. For both 2001 and 2011, n=13.

Observed Changes in Total Phosphorus

Lake TP concentrations decreased by a mean of 3.7 µg/L between 2001 and 2011. This change was not statistically significant, however (paired-samples t-test, p=0.651) (Figure 2). In both 2001 and 2011, six lakes had concentrations exceeding the 40µg/L limit required for "full support" of swimming and aesthetic uses; two of the lakes from 2001 were replaced by different lakes in 2011. Only two lakes had concentrations above the 90 µg/L partial support limit in 2001, while only one did in 2011 (Figure 3).

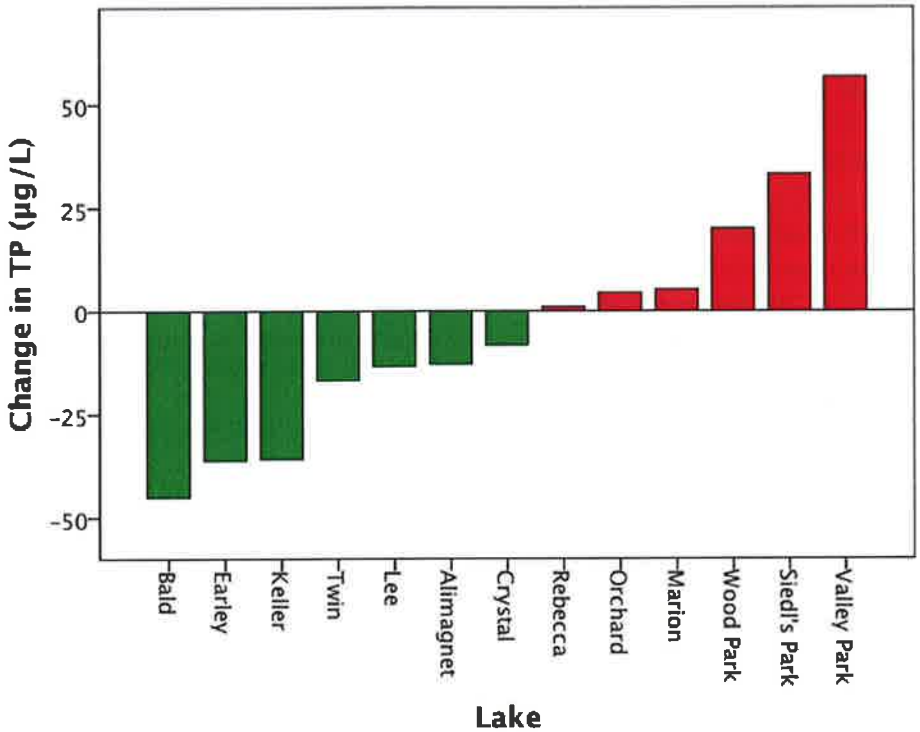

Figure 2. Changes in the mean observed summer TP concentrations of each lake between 2001-2011.

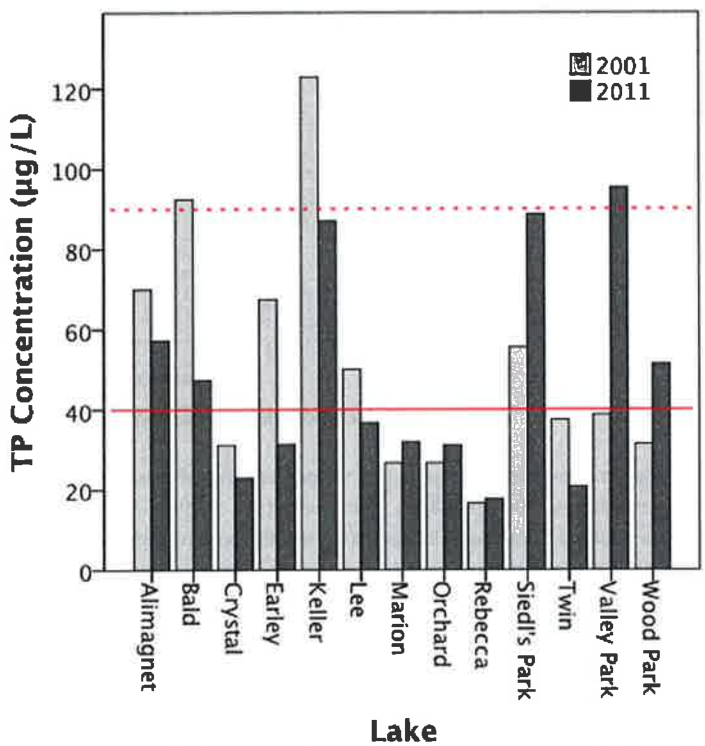

Figure 3. Mean observed summer TP concentrations of each lake in 2001 and 2011. The dashed line represents the 90 µg/L threshold for partial support of swimming and aesthetic uses; the solid line represents the 40 µg/L threshold for full support of those uses.

The Relationship between Land Development and Phosphorus Concentrations in Lakes

There was no relationship between the percent change in developed land cover in any zone from 2001 to 2011 and changes in lake TP concentrations during that same period (Figure 4). Similarly, there was no relationship between the net increase in overall LULC intensity in any zone from 2001 to 2011 and changes in lake TP concentrations during that same period (Figure 5). Initially it appeared that intensification in the 1000m zone was significantly correlated with TP concentration increases in individual lakes from 2001-2011, accounting for 42.1% of variation in the data, but this correlation was driven entirely by Wood Park Lake. When that lake was removed from the regression, no statistically significant relationship remained. The amount of intensification within each zone jumped from approximately 3.8% to 6.5% to between the 100m zone and 1000m zone (Figure 6).

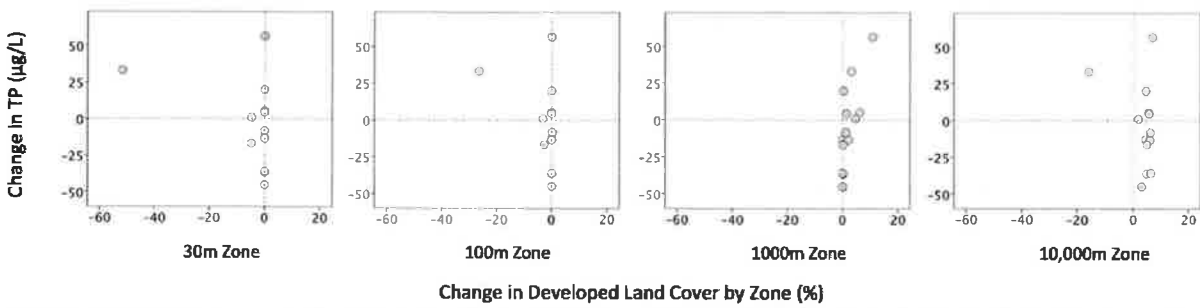

Figure 4. 2001-2011 P concentration change in lakes (µg/L) by the percent change in developed land cover in each zone over a 10 year time span.

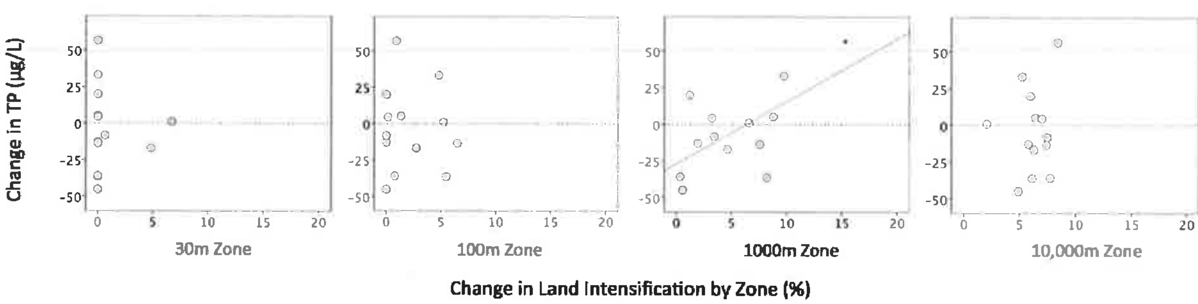

Figure 5. 2001-2011 P concentration change in lakes (µg/L) by the percent area of land within each zone that intensified in use over the same time span. Linear regression: 30m (p=0.882), 100m (p=0.851), 1000m (0.03) 10000m (p=0.658). Wood Park Lake is excluded from the 1000m zone analysis; location of its data point and the positive trend that appears when it is included are shown in red.

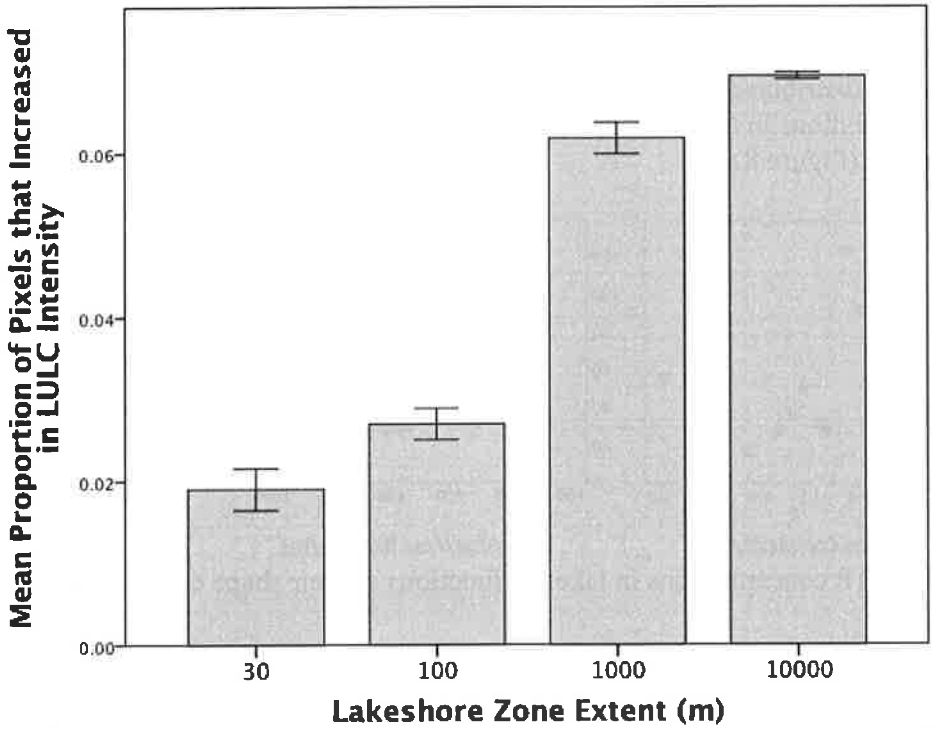

Figure 6. Mean proportion of pixels in ArcMap that increased in LULC intensity from 2001 to 2011 within each lakeshore zone. Error bars represent ± 1 SE.

The Relationship between Spatial Configuration and Phosphorus Concentrations in Lakes

Lake Shape Metrics

The FRAGSTATS mathematical model reveals no correlation between lake P levels in 2001 and any of the three lake shape metrics used at the class level: TE (linear regression, p=0.721), PARA (linear regression, p=0.993) or SHAPE (linear regression, p=0.266) (Figure 7).

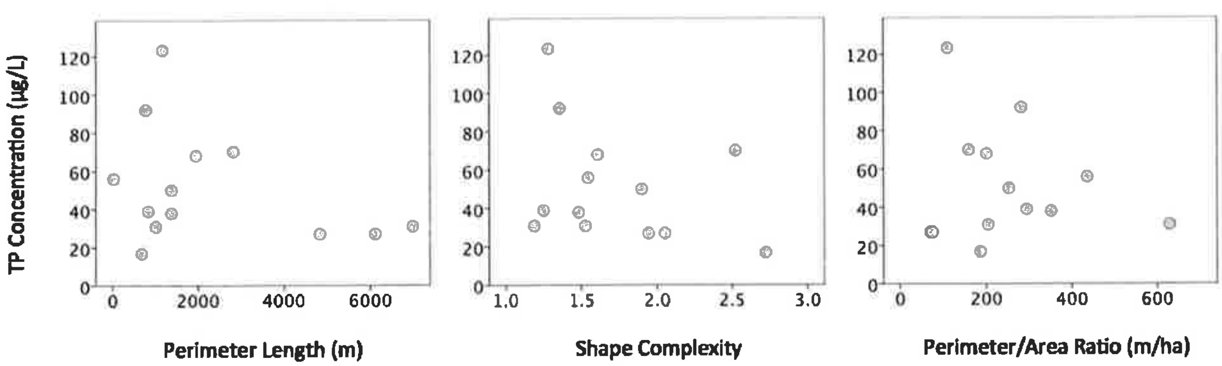

Figure 7. 2001 TP concentrations in lakes as functions of their total perimeter, shape complexity, and perimeter/area ratio.

Developed Land Shape Metrics

There was no correlation between PARA of impermeable surface at the class level and TP concentrations in lakes, but the data were not evenly distributed and could not be transformed, making it impossible to run further statistical tests. TE and CA, and ENN of impermeable cover at the class level also had no correlation with TP concentrations in lakes and were not evenly distributed. SHAPE of impermeable cover at the class level was not correlated with TP concentrations in lakes (linear regression, p=0.980) and only exhibited a slight negative trend in the data (Figure 8).

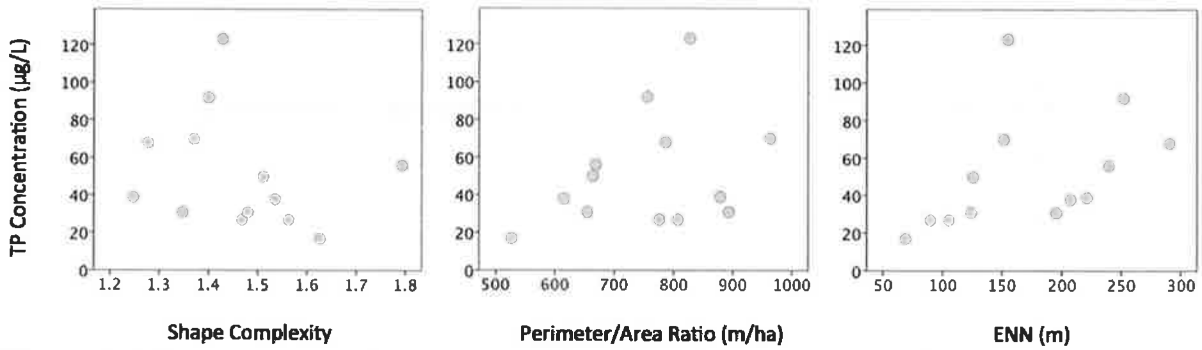

Figure 8. 2001 TP concentrations in lakes as functions of their shape complexity, perimeter/area ratio, and ENN.

Undeveloped Land Shape Metrics

Class level metrics for permeable land use classes were also not correlated with P concentrations in lakes. CA and TE once again had no correlation with P concentrations in lakes and were not evenly distributed. SHAPE of permeable surface exhibited a slightly negative relationship with P concentrations in lakes but was uncorrelated (linear regression, p=0.431). PARA exhibited a slightly positive relationship with P concentrations in lakes but was also uncorrelated (linear regression, p=0.234). ENN exhibited a positive relationship with P concentrations but was uncorrelated (linear regression, p=0.403).

The Relationship between Land Permeability and Phosphorus Levels in Rainwater Runoff

The i-Tree model held all factors constant except land cover. The land cover scenario for 2001 predicted a mean TP runoff rate of 0.087 kg/hr for the year, while the 2011 land cover scenario predicted 0.109 kg/hr. This constituted a 25.7% increase in P runoff from 2001-2011. After using i-Tree to simulate land cover in 2025, the projected mean annual TP runoff rate was 0.138 kg/hr. This constituted a 56.7% increase from 2001 (Figure 9).

The difference between projected mean annual TP runoff rates for 2001 and 2025 was statistically significant at $\alpha=0.05$ (one way ANOVA, p=0.000), while the 2011 mean was not significantly different than either the 2001 or 2025 means (one way ANOVA, p=0.230).

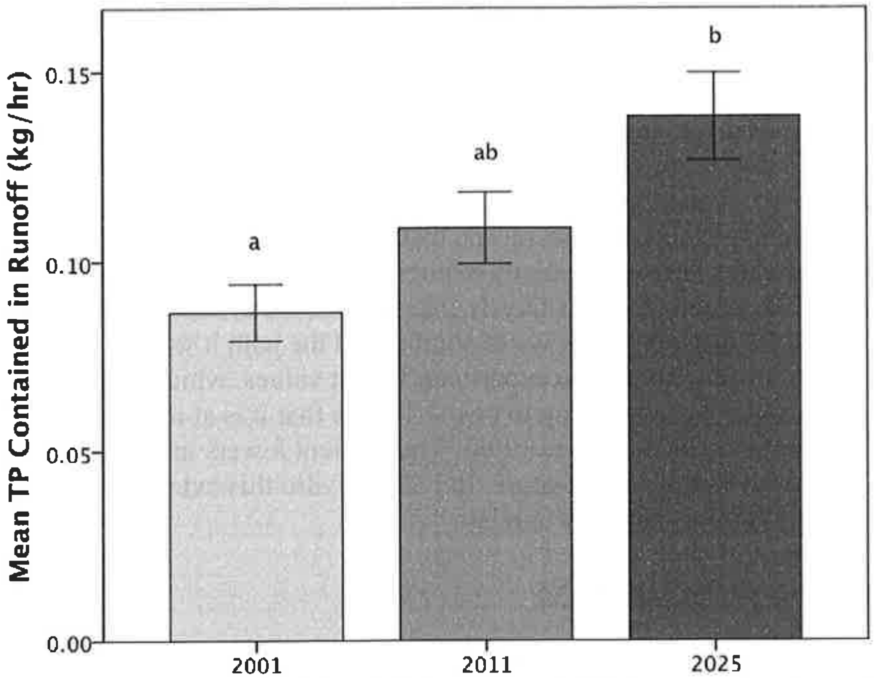

Figure 9. Mean TP contained in runoff for 2001, 2011, and 2025 as simulated by i-Tree. Means in 2001 (a) and 2025 (b) are significantly different, while the 2011 mean (ab) is not significantly different from 2001 or 2025. Error bars represent +/- 1 SE.

LIMITATIONS

Timeframe

We chose to base our study in Minnesota because it was the first state to pass P lawn fertilizer regulations. Even so, we were limited by the relatively short timeframe of ten years. Due to yearly fluctuations in P levels and the time lag between when LULC change and changes in P inputs take place and when those changes is reflected in aquatic systems, a longer time frame would have given us more consistency in average P trends and allowed sufficient time for P concentrations to change in surrounding waterways. We were also limited by the small amount of LULC change that occurred between 2001 and 2011. When we extrapolated our LULC change trends to 2025, we saw a positive correlation between LULC change and P concentrations. This suggests that if our study had a longer time frame trends that were previously insignificant would become apparent.

Spatial Metrics

Our spatial metrics were highly simplified, which made our results more clear and easier to conceptualize, but, as a result, the metrics do not contain as much detail as they could. For our calculations we grouped all land cover types into one of three categories: lake, natural, and developed. It is possible that the shape metrics for a certain degree of development, such as highly developed land are only correlated with P levels, whereas grouping all of the development together may have hidden any more nuanced correlations. We also classified agricultural land as natural land cover because it has permeable ground, but analyzing shape metrics on agricultural land may be necessary due to the high levels of nutrient inputs and land management.

The Model

Although we chose the i-Tree Hydro model because it best suited our needs for the study, it still is not perfect. Many strengths of i-Tree Hydro are also limitations. We used i-Tree Hydro as a straightforward way to model the impacts of changing a single variable: percent of impervious land cover. Although, as we have discussed, there are many benefits to this simplified approach, the simplicity also means that we must sacrifice including more detailed information and variables. Using a spatially explicit model would add an extra level of complexity and understanding to our analysis. These models can account for the location of the origin of a nutrient, the distance to the water source, and the path it will take to get there. Many models that predict nutrient runoff use export coefficient values, which means that each land cover is assigned a value corresponding to how effective that it is at retaining a given nutrient (Bennion 2005, Hanrahan 2001, Johnes 1996). The nutrient lowers in concentration as it moves from pixel to pixel toward the water feature. In i-Tree Hydro this extra precision is lost, as the land cover information is not spatially explicit.

DISCUSSION AND CONCLUSIONS

Nine years after Minnesota passed a law regulating the use of P lawn fertilizer in the TCMR, there was no overall reduction in TP concentrations in lakes within Dakota County. Because the purpose of the law was to improve water quality, it is important to note that we found no change in average P concentrations in lakes. P loading into lakes is a complex process involving a multitude of sources and pathways, so the lack of change in P concentrations in lakes after the implementation of the law suggests that other confounding variables may have a significant influence on these P concentrations.

The goal of our study was not to investigate the effectiveness of P lawn fertilizer regulations in Minnesota. Our study aimed to investigate the role of LULC change, one of the possible drivers of P concentration change in lakes, in the context of the effectiveness of the Minnesota law. If we had discovered a significant correlation between P concentrations and land use change, as we had hypothesized, we could have subtracted the corresponding change in P accounted for by LULC change from overall changes and thereby come closer to understanding the relationship between current P levels and the law. However, in each of our three sub-studies we did not find a significant correlation between LULC change and P concentrations, which does not support our initial hypothesis.

The lack of correlation between LULC change and P concentrations is a surprising finding because there is a strong body of literature linking LULC change with P concentrations (Ierodiaconou et al. 2005, Foley et al. 2005, Fraterrigo et al. 2008, Johnes et al. 1996, Soranno et al. 1996). Combined with the finding that average P concentrations have not changed significantly since the passage of P regulations in MN, it is possible that the LULC change and the passage of the law are not the primary drivers of changes in P concentrations in Dakota County.

The Relationship between Land Development and Phosphorus Concentrations in Lakes

After omitting outliers, we did not find any correlation between LULC change at any distance from lakes and TP concentration changes in those lakes. The lack of any relationship may have been because of the lack of significant land use change in our study zones, so the impact of LULC change was not large enough to become apparent in lake concentrations. We may be able to detect correlations between changes in LULC and TP levels if we were able to give this study a longer timeframe, especially because expanded time frame would more likely contain statistically significant levels of land use change. Ferris and Lehman (2008) show that the full effects of land use change on nutrient levels may not be seen for as many as eight years after the change occurs. Within a 10-year study period it may have been that be that the LULC change only for the first two years was fully accounted for, and the impacts of the more recent years will not be seen until farther into the future.

The Relationship between Spatial Configuration and P Concentrations in Lakes

We found no significant relationships between shape metrics and changes in individual lake TP concentrations. We ran a linear regression analysis on the shape complexity of impervious land around lakes in relation TP concentrations, but the slight negative relationship we found was not significant. Mayor et al. (2008) found that more complexity in the landscape is correlated with reduced runoff levels, which suggests that more complex impervious patches have a larger edge area touching previous patches, allowing more runoff and more P to be absorbed by these patches. While it would be expected that lakes near impervious patches with a larger total area would have higher levels of P runoff because there is more impervious surface for runoff to travel over, we found no correlation between CA and TP concentrations in lakes (Amiri and Nakane 2008).

Two shape metrics for pervious land cover types (CA and TE) were unevenly distributed and not correlated with TP levels in lakes. While we would expect a negative correlation between TP concentrations and both total area and total edge because higher values of both provide more opportunity for P in runoff to be absorbed before reaching lakes or rivers, we did not find such a relationship. Shape complexity once again exhibited a negative relationship with TP concentrations in lakes, aligning with the results achieved by Mayor et al. (2008). Our second complexity metric, PARA, exhibited a positive relationship with TP levels in lakes, but this relationship was insignificant. Finally, ENN was not correlated with TP concentrations but did exhibit an insignificant positive relationship with P concentrations in lakes. This suggests that as the distance from pervious patches to their nearest neighbor increases, TP concentrations in lakes do as well. Higher ENN values can also be indicative of higher fragmentation levels in landscapes which would support the findings of Zhao et al. (2012) that higher fragmentation levels of natural cover types are correlated with increased pollutant loads.

Shape metrics of the lakes themselves were not correlated with TP levels within those lakes. While we found no real relationships between shape metrics of surrounding land or lakes and TP concentrations in lakes, these results are unsurprising given that we found no correlation between LULC change and TP concentrations in lakes. These findings show that not only is LULC change an insignificant driver of lake TP level change within Dakota County, but neither is the configuration of existing land cover. Because both landscape metrics and LULC change are correlated with P concentrations in other areas (Foley et al. 2005, Fraterrigo et al. 2008, Zhao et al. 2012), it is surprising that not a single landscape metric or LULC change at any distance has proven to be related to lake TP concentrations.

The Relationship between Land Permeability and Phosphorus Levels in Rainwater Runoff

The i-Tree model did not predict a significant change in the amount of P in runoff generated between 2001 and 2011, which may provide an explanation for the lack of correlation between LULC change and observed lake TP concentrations during our study period. If LULC change did not cause a significant change in runoff concentrations, then it is not surprising that in-lake TP concentrations would not change either. Because previous studies have shown runoff and TP levels in lakes to be positively related, the i-Tree model results support our conclusion that 10 years is not a long enough timeframe to evaluate the impact of LULC change on TP concentrations in our study area. In ten years not enough LULC change occurred to observe changes in TP concentrations (Mosley 2015, Waschbusch et al. 1994).

This conclusion is further supported by the results of the 2025 scenario we ran using extrapolated LULC change values. In this scenario, the model predicted a significant increase in P in runoff. This result is in line with studies by Foley et al. 2005, Fraterrigo et al. 2008, Sorrano et al. 1996, and Wang et al. 2008 that concluded imperviousness is a significant variable for determining the the amount of P in runoff, but, similarly to our zonal study, our ten-year timescale may simply too short of a time period for that significance to become apparent.

However, the lag time after LULC change cannot take full responsibility for our lack of a significant correlation. We acknowledge that our results do not reflect our initial hypothesis and published literature regarding the impact of LULC. The positive influence on LULC and P concentrations are well studied and well understood (Ierodiaconou et al. 2005, Johnes et al. 1996, Foley et al. 2005, Fraterrigo et al. 2008, Soranno et al. 1996). Vegetation helps slow down runoff and trap and absorb the nutrients carried it carries (Hoffmann et al. 2009, Uusi-Kämppä et al. 2000, Raty et al. 2010, Schachtman et al. 1998). Conversely, impervious or developed land expedite the flow of water and transport of nutrients, increasing runoff and leading to a greater deposit of nutrients into surrounding aquatic systems (Foley et al. 2005, Fraterrigo et al. 2008). Based on robust evidence that intensifying land use increases P exports and P concentrations in lakes, we would have expect to find a significant correlation between these factors in our study, but did not.

Human Use Implications

The absence of any significant changes in TP levels has largely neutral implications for human uses of lakes, although a lack of change may be interpreted both positively and negatively depending on context. The number of study lakes with nutrient concentrations exceeding the recommended TP cap of 40 μg/L for full support of swimming and aesthetic uses remained the same from 2001-2011, although the exact makeup of that group changed. Additionally, the number of lakes exceeding the 90 μg/L cap for partial support of those uses dropped from two to one from 2001-2011. This decrease, tempered by the lack of growth in the number of lakes exceeding the full use cap, may be interpreted as a marginal gain for human lake uses in Dakota County.

However, while the overall usability of lakes as interpreted by TP concentrations did not decrease, there were also no increases in usability beyond one lake dropping below the 90 μg/L cap. This result may be interpreted negatively, as it implies that any efforts to improve lake water quality have been largely ineffective and have not resulted in an expansion of use opportunities. Thus, users may continue to be deterred by algal blooms and noxious odors (Smith and Schindler 2009), as well as fears of MC toxin exposure as based on MPCA recommendations (MPCA 2014).

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Appendix: Law Information

State laws banning phosphorus fertilizers, by effective year. From Miller 2012.

State	Minnesota	Maine	Illinois	Wisconsin	Maryland	Michigan	Vermont	New York	New Jersey	Virginia	Washington
Law	(MSA statute § 18C.60 et seq.)	38 MRSA § 419)	(415 ILCS 65)	(WSA 94.643)	(Md Laws § 6-201 et seq. and § 8-801 et seq.)	(MLCA § 324.8501 et seq.)	(10 VSA § 1266b)	(ECL § 17-2101 et seq.)	(NJSA 58:10A-61 et seq.; 4:9-15.13a)	(VA Code § 3.2-3600 et seq. and § 10.1-104.5 et seq.)	(RCWA 15.54.500)
Effective dates	2004	2008	2010	2010	2011-2013	2012	2012	2012	2013	2013	2013
Applicators affected:	All persons	All persons	"Applicator for hire" (licensed commercial, certified applicators, and others)	All persons	Everyone	All persons	All persons	All persons	All persons	All persons	All persons
Exempt applicators and allowed Phosphorus fertilizer use:	Golf courses; Sod farms; Agricultural lands and production; Phosphorus deficiency; Establish new turf	Agriculture; Phosphorus deficiency; Establish new turf; Sod farms; Turf repair; Gardening	Golf courses; Commercial and Sod farms; Agricultural lands and production; Right-of-ways; Phosphorus deficiency; Establish new turf; Lawn repair	Sod farms; Agricultural land and production; Phosphorus deficiency; Establish new turf	Agricultural purposes; Commercial and Sod farms; Phosphorus deficiency; Establish new turf; Turf repair	Golf courses; Commercial farm land; Phosphorus deficiency; Establish new turf	Golf courses; Sod farms; Agricultural lands and production; Phosphorus deficiency; Establish new turf	Gardens; Agricultural lands and production; Sod farms; Phosphorus deficiency; Establish new turf	Golf courses; Commercial Farms; Phosphorus deficiency; Establish new turf; Turf repair	Phosphorus deficiency; Establish new turf; Turf repair; Agricultural use; Gardening; Golf courses management plan	Establish new turf; Turf repair; Phosphorus deficiency; Gardens; Sod farms; Agricultural land or production
Application to paved or impervious surfaces:	Prohibited, must clean up if applied	No restrictions	Prohibited, must clean up if inadvertent	Prohibited, must clean up if inadvertent	Prohibited	Must clean up if applied	Prohibited, must clean up if applied	Prohibited, must clean up if applied	Prohibited, must clean up if inadvertent	Package label prohibits certain uses	Prohibited
Setbacks from water (buffer):	None	None	3 ft to 15 ft setback	None	10 ft to 15 ft setback	3 ft to 15 ft setback	25 ft setback	3 ft to 20 ft setback	10 ft to 15ft setback	None	None
Application on frozen and saturated soils:	No restrictions	No restrictions	Prohibited	Prohibited on frozen ground	Prohibited from Nov. 16 to Feb. 29 or on frozen ground	Prohibited	Prohibited from Oct. 16 to Mar. 31 or on frozen ground	Prohibited between Dec. 1 and Apr. 1	Prohibited during heavy rain or when predicted, on saturated or frozen ground, or from Nov. 16 - Feb. 29 (Dec. 2 - Feb. 29 for professionals)	Package label prohibits certain uses	Prohibited on frozen ground
Restrictions on Phosphorus lawn fertilizer sales:	No restrictions	Post signs about fertilizer use at point of sale	No restrictions	No display but may post sign; Must sell only for specific purposes	Must sell low Phosphorus fertilizer for lawns unless organic and sold to professional	No restrictions	Display Phosphorus fertilizer separately; Post educational signs	Display Phosphorus fertilizer separately; Post educational signs	Sale prohibited to consumers unless for deficiency, new turf, or turf repair	Sale of lawn maintenance fertilizer prohibited; Can sell existing stock	Sale prohibited unless for an allowed use and properly labeled; Can sell existing stock