

QUANTIFYING THE RELATIONSHIPS BETWEEN LAKE NUTRIENTS AND
AGRICULTURAL LAND USE/COVER AT DIFFERENT SPATIAL SCALES

By

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ABSTRACT

QUANTIFYING THE RELATIONSHIPS BETWEEN LAKE NUTRIENTS AND AGRICULTURAL LAND USE/COVER AT DIFFERENT SPATIAL SCALES

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I quantified agricultural land use/cover using five spatial metrics to determine which spatial metric was most strongly correlated with seasonal lake total phosphorus and total nitrogen concentrations in 204 Michigan lakes. I used two distance based spatial metrics, two flow direction spatial metrics and full lake catchments. Agricultural land use/cover was categorized as pasture, forage, row crop and total agriculture. My research questions were 1) which agricultural type and spatial metric is the most strongly correlated with lake nutrient concentrations, 2) How similar are the spatial metrics that quantify agricultural land use/cover in lake catchments, 3) Do the different spatial metrics each contribute to explaining lake nutrients, 4) Do different agricultural types have similar effects on lake nutrients. I used correlation coefficients to quantify the relationship between agricultural types, spatial metrics and seasonal lake TP and TN. Among agricultural types, the catchment, moderate-highly contributing area and 100 m lake-stream buffer spatial metrics were strongly correlated with each other, meaning they measured similar aspects of the landscape. Row crop and total agriculture had the strongest correlations for spring and summer lake nutrients, however, linear regression analysis within the 100 m lake-stream buffer reveal that for a change in one unit of pasture or forage, there is a larger change in lake nutrients when compared to row crop and total agriculture. Further research is needed to more fully quantify the effects of pasture and forage lands on lake nutrients.

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CHAPTER 1: QUANTIFYING THE RELATIONSHIPS BETWEEN LAKE NUTRIENTS AND AGRICULTURAL LAND USE/COVER AT DIFFERENT SPATIAL SCALES

Introduction

The effects of agriculture on lakes and streams has been well recognized for some time, and has been the focus of recent research (Arbuckle and Downing 2001, Buck et al 2004, Egerston and Downing 2004, Egerston et al 2004, Bechmann et al 2005, Bishop et al 2005, Lehmann et al 2005, Kroger et al 2007, Diebel et al 2008, Hoorman et al 2008, Gémesi et al 2011). Surface runoff from agricultural land is rich in nitrogen and phosphorus, and has been identified as the leading cause of eutrophication in lakes, reservoirs and streams (Carpenter et al 1998, Arbuckle and Downing 2001, Vanni et al 2005), resulting in excessive growth of aquatic macrophytes, algal blooms, anoxic water conditions, and undesirable fish taxa (Carpenter et al 1998, Egerston and Downing 2004, Egertson et al 2004, Vanni et al 2005). Agricultural practices are diverse, and vary by region (Vanni et al 2001, Ekholm et al 2005), however, even within regions of similar agricultural land use/cover, researchers have found high variation in surface water nutrient concentrations (Kirchner 1975, Nilsson and Hakanson 1992). There are two challenges in quantifying the effects of agriculture on surface water nutrients that likely lead to such high variation in agricultural regions. The first is that there are different types of agriculture that may influence surface waters in different ways. The second is that agricultural land use/cover can be quantified at many different spatial extents. For both of the above challenges, it is not clear which of the above factors is most related to downstream surface water nutrients.

In most studies, different types of agricultural land use/cover are lumped into a single category (Norvell et al 1979, Omernik et al 1981, Detenbeck et al 1993, Hunsaker and Levine 1995, Jones et al 2004, Gergel 2005, Baker et al 2006, Fraterrigo and Downing 2008, Zampella and Procopio 2009). However, different agricultural types have very different effects on lake and stream nutrient concentrations.

Row crops are a high-cost agricultural practice that inverts the soil and buries any vegetative residue to decay below the soil surface (Stephens 1998). Row crops are a highly researched cause of non-point source pollution due to the amounts of nutrients and fertilizers washed into streams and agricultural ditches (Bechman et al 2005, Jones and Knowlton 2005, Zaimes et al 2008). The disturbance of topsoil, repeated fertilizer applications and seasonal precipitation can result in elevated levels of nutrients and suspended solids within freshwater ecosystems, and catchments with high percentages of row crops have been noted to have high N:P ratios within streams and lakes (Arbuckle and Downing 2001, Zedler 2003, Bechman et al 2005, Jones and Knowlton 2005, Vanni et al 2005, Renwick et al 2008).

Animals grazed on pasture do not involve the increased levels of soil disturbance and fertilizer applications associated with row crops. However, grazing can cause adverse effects to freshwater ecosystems, as livestock are attracted to riparian areas and when unregulated, can result in stream bank erosion and sediment loss due to wallowing and foraging (Zaimes et al 2008). The waste produced by animals results in low N:P concentrations within streams, and is a source of concern for groundwater contamination and the threat of fecal bacteria entering drinking water (Arbuckle and Downing 2001, Monaghan et al 2008).

In comparison to row crops and pastureland, forage crops are vegetation such as hay, grain or legumes grown as a fodder provided to domestic animals (Lewis 2002). Fields that

grow forage such as alfalfa or grass have soil remain undisturbed for several years, as the crops are harvested from year to year with no need to replant seed between harvests (Lipton 1995). Harvested forage crops may be fed to animals fresh, dried or cured after ensiling (Lipton 1995, Stephens 1998). Forage crops do not contribute the same amount of soil disturbance as row crops, but require nitrogen fertilizers for increased production (Malhi et al 2004). Different agricultural types can result in different disturbance to surface water. Defining specific agricultural types may help to explain nutrient concentration variations between water-bodies with similar land use/cover (Nerbonne and Vondraek 2001, Vanni et al 2001, Ekholm et al 2005).

Agricultural land use/cover within close proximity to lakes and streams have been the focus of management studies due to concerns over erosion, nutrient loading and water quality (Dieble et al 2009, Zampella and Procopio 2009). However, many studies have found that total catchment was more relevant to quantify agricultural land use/cover and predict nutrient concentrations than buffers surrounding riparian zones or land use/cover measured near stream channels (Hunsaker and Levine 1995, Jones et al 2004, Meynendonckx et al 2006, Fraterrigo and Downing 2008, Taranu and Gregory-Eaves 2008). Hunsaker and Levine (1995) found that catchments were better at predicting nutrient concentrations than land use/cover measured in 200 m and 400 m buffers on either side of the study streams. Jones et al (2004) found the catchment scale to be the most appropriate when considering the influence of hydrology and topography on reservoir nutrient concentrations, while buffers surrounding riparian areas were unable to capture the range of variables and conditions measured in the study. Similarly, Meynendonckx et al (2006) found that stream nutrient concentrations were largely regulated by drainage characteristics and hydrological pathways of the catchment, and that land use/cover measured

close to the stream channel was not a better predictor of nitrate or phosphate concentrations than land use/cover measured at farther distances away from the stream channels.

Other studies have shown the importance of land use/cover measured near surface water, as nutrients respond differently to land use/cover measured at different scales due to variations in nutrient mobility; areas closer to water tend to contribute more to surface transport of nutrients than areas farther away (Soranno et al. 1996, Johnson et al 1997, Buck et al 2004, Diebel et al 2009). In comparison to catchment studies, narrow riparian buffers have been found to be the strongest predictor of sediments than more extensive scales (Diebel et al 2009). Johnson et al (1997) determined that land use/cover measured within the 100 m buffer strip explained variability in several chemical parameters better than whole catchment data, though noted that ecotonal areas may simply reflect dominant catchment land uses. Soranno et al (1996) found that agricultural land within 100 m of open water contributes directly to loading, and depending upon topography and runoff conditions, the greatest contribution of loading to streams came from a heterogeneous riparian corridor measuring between 0.1-6 km.

Some researchers have argued that there is no optimal scale to measure the effects of land use/cover on lakes and streams (Strayer et al 2003). Some studies showed that land use/cover values quantified at the catchment scale were strongly correlated to land use/cover values quantified at riparian scales (Arscott et al 2006, Baker et al 2006) and demonstrated that it would be difficult to separate the relative influence of near and far land uses on water quality (Zampella and Procopio 2009). Other studies have shown that configuration, i.e. the spatial aggregation of agricultural land use/cover is more important than catchment composition or measures of proximity (Gémesi et al 2011).

Uncertainty about the accuracy of distance-based spatial metrics has led to the use of empirical modeling and the development of more complex spatial metrics. Researchers combine agricultural land use/cover proximity with catchment dynamics to simulate contributing areas (Jones et al 2001, Gergel 2005, Fraterrigo and Downing 2008). Contributing area spatial metrics are developed by combining topography, hydrology and catchment variables to simulate hydrogeomorphology, and are then used to identify areas within a catchment that have the highest likelihood of contributing sediments and nutrients to surface water (Erskine et al 2006, Van Sickle and Johnson 2008).

My research builds on the results of previous studies that have used spatial metrics to quantify agricultural land use/cover, and that have defined different agricultural types and practices when predicting surface water nutrients (Jones et al 2001, Strayer et al 2003, Jones et al 2004, Buck et al 2004, Fraterrigo and Downing 2008). In this study, I compared different ways to measure spatial extent (e.g., distance-based spatial metrics, contributing-area spatial metrics and whole catchment measurements), and different agricultural types (e.g., row crop, forage, pasture, and total sum of all agricultural types) for predicting lake nutrients. My research questions are: 1) Which agricultural type and spatial metric is the most strongly correlated with lake nutrient concentrations, 2) How similar are the spatial metrics that quantify agricultural land use/cover in lake catchments, 3) Do the different spatial metrics each contribute to explaining lake nutrients, 4) Do different agricultural types have similar effects on lake nutrients

Methods

Study Region

The study area is the state of Michigan, USA (Figure 1). Michigan has three major rock types created by glacial deposits and magma: igneous rock, sediment rock, and metamorphic

rock (Brandt 2008). Bedrock geology differs by region and is covered by unconsolidated sediments such as gravel, sand, silt and silt. The bedrock of the Lower Peninsula and the eastern part of the Upper Peninsula is made of sediment rock, while the bedrock of the western part of the Upper Peninsula is made of igneous and metamorphic rock (Brandt 2009).

Michigan's state soil is Kalkaska sand (Schaetzl 2009). However, due to glacial deposits and various sediments, there is a wide variety of parent materials. The soils reflect their parent material, resulting in complex soils profiles within close proximity throughout Michigan (Schaetzl 2009). There are typically five major soil types: clay rich soils, wet sands, organic soils, loamy wet soils and sandy spodosols (Schaetzl 2009).

Michigan has 62 major watersheds with numerous inland and coastal wetlands (Wolfson 2009). There are 87,389 km of perennial streams and rivers that flow continuously due to base-flow. Eighty percent of the annual stream flow in the Lower Peninsula comes from base-flow. The base-flow provides uniform flow and relatively stable temperatures throughout the year (Wolfson 2009). Rivers maintain annual flow due to base-flow in the Upper Peninsula and the north western part of the Lower Peninsula as well. In comparison, rivers in southern part of the Lower Peninsula and thumb area of the state have lower annual flow and variable discharges due to overland flow and storm events (Wolfson 2009).

Michigan has more than 11,000 lakes > 2 ha in size, with 1000 lakes > 40 ha (Wolfson 2009, Fuller and Minnerick 2008). Inland lakes were formed by glacial processes, resulting in four basic lakes types: scour channel lakes formed by pressurized subglacial water creating small crescent filled basins; deep kettle lakes with irregularly shaped outlines and bathymetry; riverine lakes with wide floodplains; and horseshoe or oxbow lakes formed by the erosion of tributary

river channels. A rare additional type are karst lakes that are found in the northern part of the state, and are made from basins dissolved from highly soluble limestone rock (Wolfson 2009).

Michigan surface water quality varies depending on watershed characteristics; basins, geology, soils, land use/cover and human population centers (Fuller and Minnerick 2008, Wolfson 2009). Inland lakes within the Upper Peninsula and northern Lower Peninsula have good to excellent quality. In comparison, the water quality in the central and southern portions of the Lower Peninsula range from good to poor water quality, depending upon the percentage of agriculture and urban land use/cover measured in the surrounding catchment (Wolfson 2009).

Land use/cover varies throughout Michigan. The majority of agricultural land use/cover is located in the Lower Peninsula, in the middle and southwestern part of the state (Figure 1). Lakes located within the Lower Peninsula were more likely to be in close proximity to agricultural land use/cover than lakes located within the Upper Peninsula (Figure 1). The state of Michigan is an ideal location for examining research questions about agriculturally-based lake nutrient variation due to the diversity of agricultural types, the range of agricultural cover from low to high, and the high density of lakes.

Selecting study lakes

Study lakes were selected from a dataset of 364 inland lakes >14 ha, that were monitored under the Lake Water Quality Assessment Program (LWQA) (Fuller and Minnerick 2008). These lakes were sampled twice a year, spring and summer (epilimnion), from discrete water samples collected at different depths and within multiple basins from 2001-2008 (further sampling details are provided in Fuller and Minnerick 2008). Of these 364 lakes, I selected those that had at least 1 % of their catchment in total agricultural cover, and that had no more than 25% of the 500 m buffer in urban land use/cover. The resulting dataset contained 204 lakes located in

both the Lower and Upper Peninsulas (Table 1, Figure 2). Lakes used for analysis had surface area between 14 ha – 4,200 ha, and mean depth between 0.8 m – 20.5 m (Table 1, Figure 2). These selection criteria were used to first, ensure that at least some agriculture occurred in the catchment, to avoid excessive data points with zero agricultural land use/cover; and second, to remove the potentially large effects of urbanization that may mask patterns with agricultural land cover. We used the 500 m buffer to quantify urban land use/cover due to the amount of urban and suburban land use/cover concentrated in the areas around lakes (Walsh et al. 2000), thus providing more information about urban land use/cover than measured in a catchment-wide extent.

Agricultural land use/cover

I used the 2007 USDA Agricultural Statistics (NASS) Crop Data Layer (CDL) to quantify land use/cover. The Remote Sensing & GIS Research and Outreach Services (RS&GIS) assisted converting the CDL raster data (56 m X 56 m) with 72 land use/cover categories into a vector format with 13 main categories based off of defined uses (urban, agricultural, forest, etc.). Agricultural land use/cover types within the CDL were categorized using general use, planting and harvest practices into four classes; pasture, forage, row crop and total agriculture (all agricultural types combined) (Stephens 1998, Lewis 2002, House 2006, Zaimes et al 2008).

Distance based spatial metrics

Buffers are commonly used for water quality spatial analysis in relation to land use/cover, but it is not always clear what the optimal width should be (Stephenson and Morin 2009). I chose two different buffer distances to test the relationship between agricultural land use/cover and lake nutrient concentrations (Table 2, Figure 1). First, I created a 500 m equidistant buffer

around lake shorelines. Second, I created a 100 m equidistant buffer around streams that flow into the lake and the lake shoreline itself. I used the National Hydrology Dataset (NHD) at 1:24,000 resolution for the stream network and a lake polygon layer from the Michigan Department of Natural Resources (MDNR) for the lake shorelines.

Flow direction spatial metrics

Two different spatial metrics were created using flow path estimates using the flow direction D8 algorithm (Erskine et al 2006) and the USGS National Elevation Dataset (NED) at 30 meter resolution. Flow direction was calculated using the ESRI Spatial Analyst Hydrology tools within ArcGIS to determine the flow of water to the lowest lying areas within a lake catchment. I selected parameters to create two different spatial metrics, which I will refer to as contributing areas, or those areas that can potentially produce runoff to the location (i.e., a grid cell) (Erskine et al 2006) to simulate hydrogeomorphology within the catchment. One of the metrics represented highly contributing areas, which included those cells that have a flow accumulation greater or equal to 100,000 pixels within the grid; those cells that were connected to upstream cells or had the highest number of cells that drained into a singular cell, i.e. the lowest –lying areas within the grid and so have the potential to be focal areas of nutrient transport. The second metric represented moderate-highly contributing areas, which included the same cells in the highly contributing area that have a flow accumulation greater or equal to 100,000 pixels within the grid, and also the additional cells that had flow accumulation greater or equal 75,000 pixels within the grid, or moderate amounts of upstream cells flowing into them. The parameters were chosen by visual inspection of cell contributing area maps to arrive at contrasting sizes of contributing areas. The highly contributing areas are the lowest lying areas within lake catchments, and often closely follow the stream flow-lines (Table 2, Figure 1). In comparison,

the moderate-highly contributing area captures additional land use/cover that extends beyond streams and the highly contributing area, and includes more areas that may contain ephemeral stream beds and drainage lines on the land (Table 2, Figure 1).

Catchment delineations and metric

Catchments were delineated using existing watershed features created for stream catchments from the Michigan Department of Natural Resources (MDNR) and hand-digitizing the coverage for modifications needed for lake catchments using the USGS Digital Raster Graphic Mosaic (DRG) coverage. The NHD stream coverage was used to determine connected streams and catchments flowing into lakes. Lake catchments were defined as all land and streams draining into the lake with upstream lakes < 10 ha in area. If a lake > 10 ha was upstream and connected to the downstream lake, then the downstream lake catchment did not include the catchment of the upstream 10 ha lake. This criterion was established to attempt to create ‘local’ catchments that included the area of land and streams that drained into a lake and was not unduly influenced by upstream lakes.

Statistical analysis

I calculated Pearson correlation coefficients (significance $\alpha \leq 0.05$), between the four agricultural types and spring and summer TP and TN to compare the relationships between nutrients, different spatial extents and agricultural types. I then examined whether the agricultural types and metrics themselves were correlated with each other by calculating Pearson correlation coefficients among the spatial metrics and the agricultural types themselves.

For those spatial metrics that were strongly correlated with each other and that were also strongly correlated to lake nutrients, I conducted a regression residual analysis to determine if the two different spatial extents provided new predictive capability or were equally providing the

same information about agricultural cover. For this analysis, I ran regressions among each of the nutrients and the spatial scales that were strongly correlated and calculated the residuals from the regression. I regressed the residuals against the agricultural variable that was also strongly correlated to a lake nutrient to see if additional variation in lake nutrients as explained by the other agricultural variable. Finally, to examine whether the slopes between seasonal nutrients and agricultural types were similar, I conducted a linear regression analysis between total agriculture, row crop, forage and pasture measured within the 100 m lake-stream buffer with spring TP and TN.

Results

Study lakes

The study lakes are widely distributed throughout Michigan (Figure 2) and they had a wide range in water chemistry, surface area, catchment area and lake depth (Table 1). Spring TP concentrations ranged from 1 to 176 $\mu\text{g L}^{-1}$ and summer TP concentrations ranged from 1 to 290 $\mu\text{g L}^{-1}$ (Table 1). Spring TN concentrations ranged from 146-7,800 $\mu\text{g L}^{-1}$, and summer TN concentrations ranged from 90-3,180 $\mu\text{g L}^{-1}$ (Table 1). However, the median values for spring and summer nutrient concentrations were at the lower end of the concentration range.

Agricultural land use/cover around the study lakes

The percentage of agricultural cover was highly variable as measured by the spatial metrics. The 100 m lake-stream buffer had the lowest maximum percentages measured for the agricultural types except for forage, which had a similar range for all of the spatial metrics. In comparison, the highly contributing area had the highest maximum percentage measured for the

agricultural types, except for forage, which tied with forage within the moderate-highly contributing area (Table 2). The median percentage value for row crop measured in the catchment was <6% for the study lakes. However, some of the study lakes had very high percentages of row crop within the catchment (Table 2). The pattern of high maximum values for agriculture percentages with low median values were repeated for all of the spatial metrics (Table 2).

Relationships between metrics of agriculture land use/cover and lake nutrients

Correlation strengths for TP and TN concentrations varied for the spatial metrics, depending on season and agricultural type. The 100 m lake-stream buffer, moderate-highly contributing area, and catchment were strongly correlated to Spring TP and TN for all three agricultural types and total agriculture (Table 3a). Additionally, for spring TN, strong correlation strengths were found for row crop and total agriculture (Table 3a).

Relationships between agricultural land use/cover types

The strongest correlations among total agriculture and the three agricultural types were between total agriculture and row crop ($r \geq 0.90$) (Table 4). Total agriculture had moderate to strong correlations with forage and pasture for all of the spatial metrics, except the moderate-highly contributing area and catchment metrics. The weakest correlations were between pasture, forage and row crop for the highly contributing area and moderate-highly contributing area ($r < 0.30$) (Table 4).

Relationships among spatial metrics within individual agricultural types

The strongest correlations were between the catchment, moderate-highly contributing area and highly contributing area (Table 5). The weakest correlations were between the 100 m lake-stream buffer and 500 m lake buffer (Table 5). The range in spatial metric correlation

strengths and the results from Table 3a and 3b indicate that differences may result from the wide range of values across the datasets for local agricultural land use/cover (Table 1, Table 3a, Table 3b). Next, I examined whether the catchment metrics contribute the same information to the relationship with lake nutrients, or if some of the spatial metrics are providing additional information related to land use/cover that helps to further explain lake nutrient concentrations. I explored such relationships between two sets of spatial metrics below.

100 m lake-stream buffer vs. catchment: The 100 m lake-stream buffer and catchment were strongly correlated to both spring and summer lake nutrients (Tables 3a and 3b). There was a strong positive correlation between the 100 m lake-stream buffer and catchment spatial metrics for total agriculture and row crop (Table 5, Figure 3). Agricultural percent cover was higher in the catchment compared to the 100 m lake-stream buffer (Figure 3), suggesting that although the two metrics were correlated, the distribution of agricultural land use/cover in lake catchments is not uniform, and agricultural land use/cover within the 100 m lake-stream buffer is less common than in the rest of the catchment. To attempt to separate the possible effects of the two spatial metrics, I first ran regressions of lake nutrients against the catchment spatial metric; then I regressed the residuals from this model on lake nutrients. The fact that this latter correlation was significant for spring and summer TP, and spring TN shows that the 100 m lake-stream buffer helps to explain additional variation in lake nutrients (Figure 4).

100 m lake-stream buffer vs. moderate-highly contributing area: The 100 m lake-stream buffer and moderate-highly contributing area were weakly correlated with spring and summer TP, and moderately correlated with spring and summer TN (Tables 3a and 3b). There was a strong positive correlation between both spatial metrics for total agriculture and row crop (Table 5, Figure 5). Agricultural land use/cover was higher overall in the moderate-highly contributing

area compared to the 100 m lake-stream buffer (Figure 5). I found that the 100 m lake-stream buffer gives information in addition to that which was explained by the moderate-highly contributing area. The correlation between the moderate-highly contributing area residuals and the 100 m lake-stream buffer was significant for both TP and TN for both seasons (range in r from 0.15 to 0.30) (Figure 6).

Catchment vs. moderate-highly contributing area: Both spatial metrics have similar relationships with the 100 m lake-stream buffer, and were moderately correlated with seasonal lake nutrient concentrations (Tables 3a and 3b). There was a strong positive correlation between the catchment and moderate-highly contributing area for total agriculture and row crop (Table 5, Figure 7). Percentages of total agriculture and the three agricultural types were higher in the catchment compared to the moderate-highly contributing area (Figure 7). The very strong correlation between the two spatial metrics suggests that they capture the same amount and spatial pattern of land use/cover, or that within both spatial metrics the measured spatial patterns are very similar. The lack of a significant correlation between the catchment residuals with the moderate-highly contributing area suggests that this metric is not providing additional information beyond the catchment (Figure 8).

Linear regressions between spring nutrients and agricultural types: I compared the slopes of the relationships between agriculture cover and land nutrients by examining spring nutrients and the 100 m lake-stream buffer only. I found that row crop and total agriculture had similar slopes for spring TP and TN, whereas pasture and forage had larger slopes than row crop and total agriculture. Thus, there was a larger increase in TP and TN for forage or pasture per unit increase in cover compared to row crop and total agriculture (Figures 9, 10).

Comparisons across seasons: Correlation strengths between agricultural types and nutrient concentrations varied for the spatial metrics depending upon season (Tables 3a, 3b). The 100 m lake-stream buffer, highly contributing area, moderate-highly contributing area, and catchment had relatively strong correlations ($r > 0.50$) with spring TN for row crop and total agriculture, but were moderate to weakly correlated with pasture or forage (Table 3a). The 100 m lake-stream buffer, moderate-highly contributing area and catchment had low correlations ($r > 0.30$) with spring TP for forage, row crop and total agriculture, but had overall moderate to weak correlations ($r < 0.50$) for spring TN (Table 3a). Correlation strengths were moderate to weak ($r < 0.50$) between all five spatial metrics and agricultural types for summer TP and TN (Table 3b). The strongest correlations were between the 100 m lake-stream buffer, highly contributing area, moderate-highly contributing area, and catchment with summer TN for row crop and total agriculture.

Discussion

I took a unique approach in my study by comparing spatial metrics that have been traditionally used for stream studies to quantify different agricultural types to predict lake nutrients. I found that differences in the relationships between agricultural spatial metrics and lake nutrients depended upon season, nutrient, and dominant agricultural type. However, despite differences, some common patterns emerged. Row crop and total agriculture were strongly correlated with one another, as 50-70% of total agriculture consists of row crop across all study lake catchments. This suggests that row crop is the dominant agricultural type measured around selected study lakes, and may have the most impact on lake nutrient concentrations. The 100 m lake-stream buffer and catchment were moderate to strongly correlated among the three

agricultural types and total agriculture. In comparison, the catchment and moderate-highly contributing area spatial metrics were also strongly correlated, with further analysis indicating that the spatial metrics were likely measuring similar aspects of catchment agricultural land use/cover. More importantly, my analysis shows that several of the spatial scales were strongly correlated with one another, and even though there were some differences among the different spatial metrics, no single scale stood out as the best at predicting lake nutrients.

Correlations among agricultural types and total agriculture

Few studies have separated out the influence of individual agricultural types on surface water nutrients (Johnson et al 1997, Strayer et al 2003, Buck et al 2004, Meynendonckx et al 2006, Diebel et al 2009). Studies will often define different agricultural types, but often lump them together as total agriculture or cropland when analyzing the impact of land use/cover on surface water (Osborne and Wiley 1988, Soranno et al 1996, Ahearn et al 2005, Arscott et al 2006, Taranu and Gregory-Eaves 2008, Gémesi et al 2011). Other studies measure all agriculture within the landscape as one category of land use/cover, without distinguishing the agricultural types or practices make up the category (Norvell et al 1979, Omernik et al 1981, Detenbeck et al 1993, Hunsaker and Levine 1995, Jones et al 2004, Gergel 2005, Baker et al 2006, Fraterrigo and Downing 2008, Zampella and Procopio 2009). Separating out the possible effects of different agricultural types on lake nutrients was an important goal for this study. Different agricultural practices have been noted to have very different effects on water body nutrient concentrations (Nerbonne and Vondraek 2001), and defining specific agricultural practices may help to explain nutrient concentration variations between water-bodies with similar land use/cover (Nerbonne and Vondraek 2001, Vanni et al 2001, Ekholm et al 2005). My results show that row crop and total agriculture had the strongest correlation with spring and

summer TN, and weaker correlations with spring and summer TP depending on the spatial metric (Tables 3a, 3b).

Relationships between agricultural spatial metrics and lake nutrients

I compared commonly used spatial metrics in an attempt to determine which spatial metric, if any, was the best at predicting lake nutrient concentrations (Tables 3a, 3b). The 100 m lake-stream buffer, moderate-highly contributing area, and catchment had the strongest correlations with TP and TN for all three agricultural types and total agriculture (Table 3a). Previous studies have observed strong correlations between surface water nutrient concentrations and land use/cover quantified within close proximity of surface waters (Soranno et al 1996, Johnson et al 1997, Diebel 2009), or with land use/cover measured at the catchment scale (Hunsaker and Levine 1995, Jones et al 2004, Meynendonckx et al 2006, Fraterrigo and Downing 2008, Taranu and Gregory-Eaves 2008). Other studies have emphasized the importance of landscape arrangement, topography, and the amount of detail provided by contributing areas and simulated models to predict nutrients (Hunsaker and Levine 1995, Gergel 2005, Baker et al. 2006). Many studies have quantified agricultural land use/cover at various scales and measured their effects on stream nutrient concentrations (Omernik et al 1981, Osborne and Wiley 1988, Hunsaker and Levine 1995, Strayer et al 2003, Baker et al 2006, Meynendonckx et al 2006, Diebel et al 2009, Zampella and Procopio 2009). In comparison, relatively few studies have examined the relationships between fixed-distance spatial metrics and contributing areas to predict nutrients within reservoirs (Jones et al 2004, Gémesi et al 2011) or lakes (Norvell et al 1979, Taranu and Gregory-Eaves 2008). My results suggest that many of the spatial metrics are correlated and that in similar landscapes to Michigan, any of several extents would work equally well at predicting lake nutrients. However, other studies have shown that

agricultural types predict nutrients differently depending on the scale used to measure land use/cover (Buck et al 2004) and the season in which they are measured (Vanni et al 2001, Bechman et al 2005, Diebel et al 2009).

Other studies have found that the fluctuations in nitrogen and phosphorus concentrations can be caused by different types of agricultural land use/cover and seasonal precipitation (Vanni et al 2001, Bechman et al 2005). Possibilities for TN variability between spring and summer have been well established due to complexities of the nitrogen cycle, local agricultural types, hydrology and seasonal precipitations. Kroger et al (2007) noted fluctuations in nitrogen concentrations due to temperature dependency for microbial immobilization and denitrification, plant assimilation, seasonal precipitation and storm events. Likewise, Bechmann et al (2005) found that internal lake processes, such as light, temperature and algal uptake of phosphorus significantly influenced the concentrations and availability of phosphorus within the water column. The uptake of phosphorus and nitrogen during summer months may explain the weak correlations found between spatial metrics and summer TN and TP (Table 3b).

Relationships among agricultural spatial metrics

My results showed that more than one spatial metric was strongly correlated with lake nutrients (Tables 3a, 3b), which is supported by studies that have conflicting results in regards to which is the best scale to quantify land use/cover (Hunsaker and Levine 1995, Soranno et al 1996, Johnson et al 1997, Jones et al 2004, Gergel 2005, Baker et al 2006, Meynendonchx et al 2006, Fraterrigo and Downing 2008, Taranu and Gregory-Eaves 2008, Dibel 2009). Since there is more than one spatial metric that is strongly correlated with lake nutrients for agricultural types, it is therefore necessary to determine how strongly correlated those spatial metrics are with one another (Table 5).

My results showed that the 100 m lake-stream buffer and catchment have similar correlation strengths with nutrients for all three agricultural types and total agriculture (Table 3a, 3b) and are strongly correlated with each other for each agricultural type (Figure 3). However, the results from the residual analysis show that the 100 m lake-stream buffer helps to explain additional variation in lake nutrients beyond what the catchment explains (Figure 4). I found similar results for the moderate-highly contributing area and the 100 m lake-stream buffer (Figure 5). However, it appears that the moderate-highly contributing area and the catchment measure nearly identical amounts of agricultural cover and so do not predict unique amounts of lake nutrient variation (Figures 7, 8).

Other studies have found that different spatial metrics are strongly correlated with one another, and that there are often difficulties in separating out the relative influence of near and far land use/cover on water quality (Zampella and Procopio 2009). Arscott et al (2006) used numerous spatial metrics to predict nutrients in reservoirs and streams, and found that land use/cover quantified at the catchment scale were strongly related to land use/cover quantified within buffers around riparian areas. Likewise, Baker et al (2006) found that agricultural land use/cover measured within fixed-distance buffers around riparian areas were strongly correlated with whole-catchment land use/cover, stating that land use/cover measured within the buffer cannot reveal much about nutrient flux that is not already captured by the catchment.

Strayer et al (2003) showed that there was not a single optimal scale for quantifying the effects of land use/cover on stream nutrients for empirical models. In addition, Gergel (2005) showed that landscape arrangement, i.e. the general pattern of land use/cover throughout the catchment coupled with topography may be the most important variables to consider when measuring land use/cover in relation to non-point source pollution. Recent studies, such as

Gémesi et al (2011) show that catchment configuration (i.e., spatial arrangement of agricultural land use/cover) was more important than composition (i.e., percent composition of land use/cover types) at either catchment or riparian scales. Evidence from other studies, coupled with results that spatial metrics are strongly correlated with one another among different agricultural types and with lake nutrients, indicates that there may not be a single spatial metric that best predicts lake nutrients.

Effect size of different agricultural types

Because total agriculture was comprised of 50-70% row crop within each spatial metric (Table 2), row crops are likely contributing the most nutrients to lakes. However, it is important to compare the effect sizes of each of the agricultural types (i.e., the slopes of the relationships) to determine if different agricultural types have the same effect per unit increase in area. I quantified univariate regressions of each of the nutrients and seasons against the different agricultural types in the 100 m lake-stream buffer. I chose the 100 m lake-stream buffer because this scale was consistently correlated with both nutrients and seasons. I found that the slopes for forage and pasture are much steeper compared to row crops and total agriculture (Figures 9, 10). These results suggest that lake nutrients react more quickly to pasture and forage than to row crop, i.e. there is a larger increase in TP and TN for every increased unit of pasture and forage. The percentage of row crop measured within the 100 m lake-stream buffer was higher than either pasture or forage (Table 2). However, the linear regressions results indicate that forage and pasture land use /cover could potentially have a stronger influence on lake nutrients if the percentage of either land use/cover increased. These results are somewhat preliminary because in my catchments, the percentages of forage and pasture were relatively low, so the regressions

for these types are not as well defined as they are for row crop. This result warrants further investigation in catchments with higher proportions of forage and pasture.

However, there is evidence from the literature supporting the overall pattern that I found. As stated previously, the influence of row crops on surface water is well known and has become the focus of management and conservation practices to prevent excess nutrients from entering waterways (Arbuckle and Downing 2001). In comparison, forage crops and pasture cover are very efficient at nutrient utilization and are not associated with the same amount of soil erosion and agrichemical runoff as row crops. However, sediment loss and stream bank erosion due to unregulated access of cattle is a known source of excess nutrients in surface water (Zaimes et al 2008). Excessive fertilizers on forage and pasture grass are also known to leach to surface runoff and are a particular problem on steep slopes in late growing seasons (Doo Hong Min 2002). Forage crops and pastures require the application of fertilizers based off of soil test results , but without proper attention to crop health and management considerations, the crops can decrease in fertility, resulting in cover loss and increased erosion and runoff (Daniels et al 2011). A combination of steep topography, proximity, excessive fertilizer applications and unregulated management practices may help to explain why lake nutrients react more quickly for forage and pasture than with row crop and total agriculture when measured in the 100 m lake-stream buffer. The influence of pasture and forage may be strong on lake nutrients, but the magnitude of their effects are difficult to quantify because these lands are less common across the landscape.

Conclusions

Recommendations for quantifying land use/cover around lakes

I found little statistical differences among the spatial metrics. Quantifying land use/cover in relation to lake nutrients can be a challenge for scientists and managers due to the complexities of the systems they are analyzing, as well as constraints from the time and cost of collecting data. As stated previously, many fresh water studies analyze either land within close proximity to water bodies, or land throughout the catchment. Due to the time and cost constraints of digitizing lake catchments, my results support measuring agricultural land use/cover at the 100 m lake-stream buffer. Even though the 100 m lake-stream buffer helps to explain additional variation in lake nutrients, both the catchment and the 100 m lake-stream buffer are measuring similar features of the agricultural land use/cover.

Total agriculture and row crop had strong to moderate correlations with spring TN, which is supported by many other studies. Pasture and forage had weak correlations with lake nutrients for all five of the spatial metrics when compared to row crop and total agriculture. However, scientists and managers should not disregard the impacts of pasture and forage types when analyzing the cumulative effects of agricultural land use/cover on lake nutrients concentrations; even though pasture and forage make up a small percentage of measured land use/cover in the lake catchments, their impacts may be overshadowed by the prevalence of row crop in an analysis such as this. Further research is needed to more fully quantify the effects of pasture and forage lands on lake nutrients.

Table 1. Summary statistics of the lake variables. TP is total phosphorus, TN is total nitrogen. N= 204 lakes.

Variable	Minimum	Maximum	Median
Surface area (ha)	14	4,183	75
Catchment area (ha)	52	241,640	769
Mean depth (m)	0.8	21	5
Maximum depth (m)	3.0	39	13
TP, spring ($\mu\text{g L}^{-1}$)	1	176	16
TP, summer ($\mu\text{g L}^{-1}$)	3	290	12
TN, spring ($\mu\text{g L}^{-1}$)	146	7,800	655
TN, summer ($\mu\text{g L}^{-1}$)	90	3,180	575

Table 2. Summary statistics of the percentage of agricultural types for each spatial metric. N = 204 lakes.

Spatial metric	Minimum	Maximum	Median
<i>Lake-stream buffer, 100 m</i>			
Pasture	0	16	3
Forage	0	23	2
Row crop	0	46	1
Total agriculture	0	53	4
<i>Buffer, 500 m</i>			
Pasture	0	19	3
Forage	0	18	1
Row crop	0	47	3
Total agriculture	0	60	7
<i>Contributing area, highly</i>			
Pasture	0	52	3
Forage	0	24	2
Row crop	0	65	4
Total agriculture	0	66	9
<i>Contributing area, moderate-highly</i>			
Pasture	0	22	4
Forage	0	24	20
Row crop	0	57	6
Total agriculture	0	65	12
<i>Catchment</i>			
Pasture	0	21	5
Forage	0	27	2
Row crop	0	61	6
Total agriculture	1	70	17

Table 3a. Correlations between spring lake total phosphorus (TP) or total nitrogen (TN) concentrations and the different spatial metrics. Numbers in bold are either the highest correlation value, or within 0.05 of the highest value within the respective column. All values in the tables are significant at $\alpha \leq 0.05$. N= 204 lakes.

Spatial metric	TP Pasture	TP Forage	TP Row crop	TP Total agriculture	TN Pasture	TN Forage	TN Row crop	TN Total agriculture
Lake-stream buffer, 100 m	0.33	0.42	0.32	0.41	0.44	0.42	0.65	0.69
Lake buffer, 500 m	0.26	0.25	0.30	0.34	0.23	0.22	0.43	0.45
Contributing area, highly	0.17	0.33	0.27	0.32	0.22	0.23	0.57	0.60
Contributing area, moderate-highly	0.20	0.39	0.32	0.36	0.24	0.30	0.64	0.65
Catchment	0.23	0.40	0.33	0.40	0.20	0.30	0.60	0.66

Table 3b. Correlations between summer lake total phosphorus (TP) or total nitrogen (TN) concentrations and the different spatial metrics. Numbers in bold are either the highest correlation value, or within 0.05 of the highest value within the respective column. All values in the tables are significant at $\alpha \leq 0.05$. N= 204 lakes.

Spatial metric	TP Pasture	TP Forage	TP Row crop	TP Total agriculture	TN Pasture	TN Forage	TN Row crop	TN Total agriculture
Lake-stream buffer, 100 m	0.21	0.25	0.28	0.33	0.32	0.36	0.39	0.44
Lake buffer, 500 m	0.18	n.s.	0.11	0.17	0.16	0.26	0.32	0.34
Contributing area, highly	n.s.	0.39	0.31	0.34	0.19	0.30	0.44	0.44
Contributing area, moderate-highly	0.15	0.20	0.24	0.26	0.21	0.25	0.44	0.47
Catchment	0.17	0.21	0.22	0.27	0.19	0.26	0.45	0.49

Table 4. Correlations between different agriculture types within each spatial metrics. All values in the tables are significant at $\alpha \leq 0.05$, 'n.s.' is not significant. N= 204 lakes. Note that the value in the columns are measured at the same spatial extent as the value in the row.

Spatial metric	Pasture	Forage	Row crop	Total agriculture
<i>Pasture</i>				
Lake-stream buffer, 100 m	-	0.39	0.34	0.61
Buffer, 500 m	-	0.36	0.42	0.67
Contributing area, highly	-	0.19	0.29	0.54
Contributing area, moderate-highly	-	0.33	0.37	0.60
Catchment	-	0.36	n.s.	0.61
<i>Forage</i>				
Lake-stream buffer, 100 m		-	0.40	0.64
Buffer, 500 m		-	0.30	0.63
Contributing area, highly		-	0.27	0.53
Contributing area, moderate-highly		-	0.17	0.46
Catchment		-	n.s.	0.45
<i>Row crop</i>				
Lake-stream buffer, 100 m			-	0.93
Buffer, 500 m			-	0.91
Contributing area, highly			-	0.93
Contributing area, moderate-highly			-	0.94
Catchment			-	0.94
<i>Total agriculture</i>				
Lake-stream buffer, 100 m				-
Buffer, 500 m				-
Contributing area, highly				-
Contributing area, moderate-highly				-
Catchment				-

Table 5. Correlations between different spatial metrics within each agricultural type. All values in the table are significant at $\alpha=0.05$. N= 204. 'Mod.- high.' is moderate-highly. Note that the value in the columns are measured for the same agricultural type as the value in the row.

Spatial metric	Lake-stream buffer, 100 m	Buffer, 500 m	Contributing area, highly	Contributing area, mod.-high.
<i>Pasture</i>				
Lake-stream buffer, 100 m	-	-	-	-
Buffer, 500 m	0.38	-	-	-
Contributing area, highly	0.38	0.53	-	-
Contributing area, moderate-highly	0.47	0.62	0.74	-
Catchment	0.45	0.78	0.68	0.94
<i>Forage</i>				
Lake-stream buffer, 100 m	-	-	-	-
Buffer, 500 m	0.22	-	-	-
Contributing area, highly	0.49	0.57	-	-
Contributing area, moderate-highly	0.57	0.64	0.73	-
Catchment	0.56	0.66	0.70	0.97
<i>Row crop</i>				
Lake-stream buffer, 100 m	-	-	-	-
Buffer, 500 m	0.44	-	-	-
Contributing area, highly	0.80	0.50	-	-
Contributing area, moderate-highly	0.76	0.64	0.90	-
Catchment	0.75	0.70	0.86	0.98
<i>Total agriculture</i>				
Lake-stream buffer, 100 m	-	-	-	-
Buffer, 500 m	0.46	-	-	-
Contributing area, highly	0.70	0.63	-	-
Contributing area, moderate-highly	0.73	0.73	0.88	-
Catchment	0.71	0.77	0.83	0.98

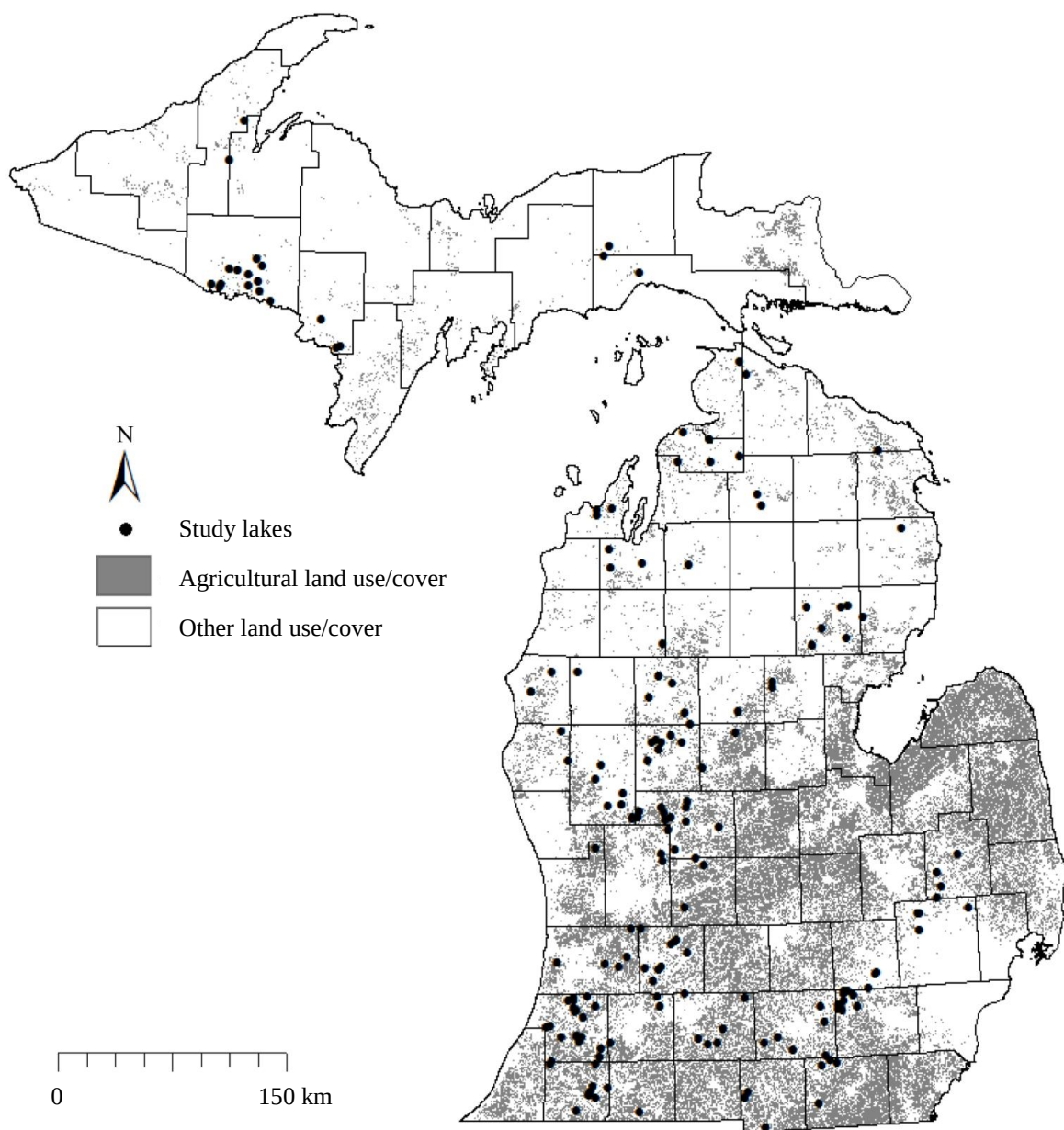


Figure 1. Distribution of the 204 lakes used in this study. All types of agricultural land use/cover are shown in grey.

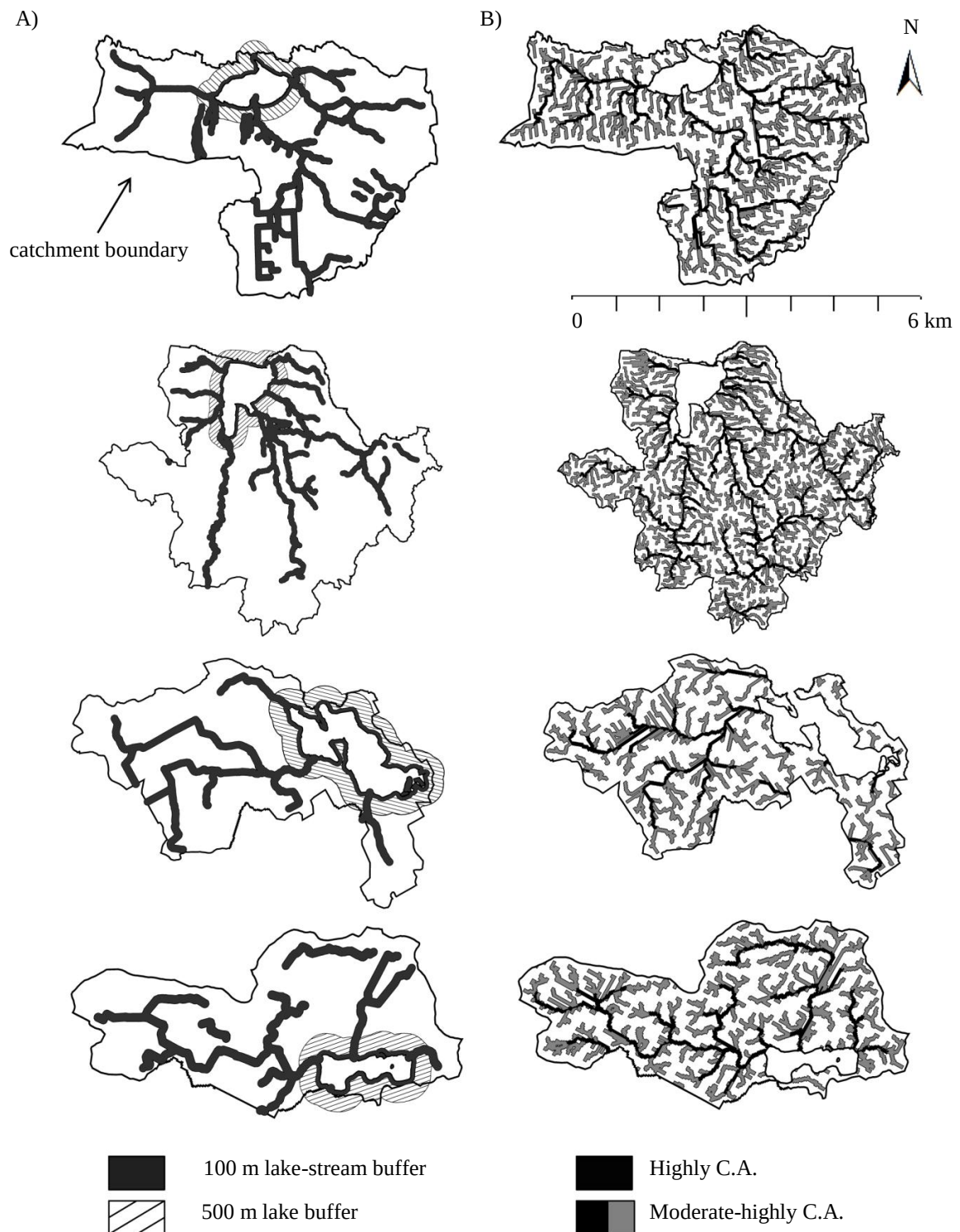


Figure 2. Four different study lakes displaying the five spatial extents used to measure agricultural land use/cover within lake catchments. Column A) equidistant buffers around either lakes and streams, or lakes only, and column B) contributing areas estimated at highly contributing or moderate-highly contributing areas, as well as the full catchment area. 'C.A.' is contributing area.

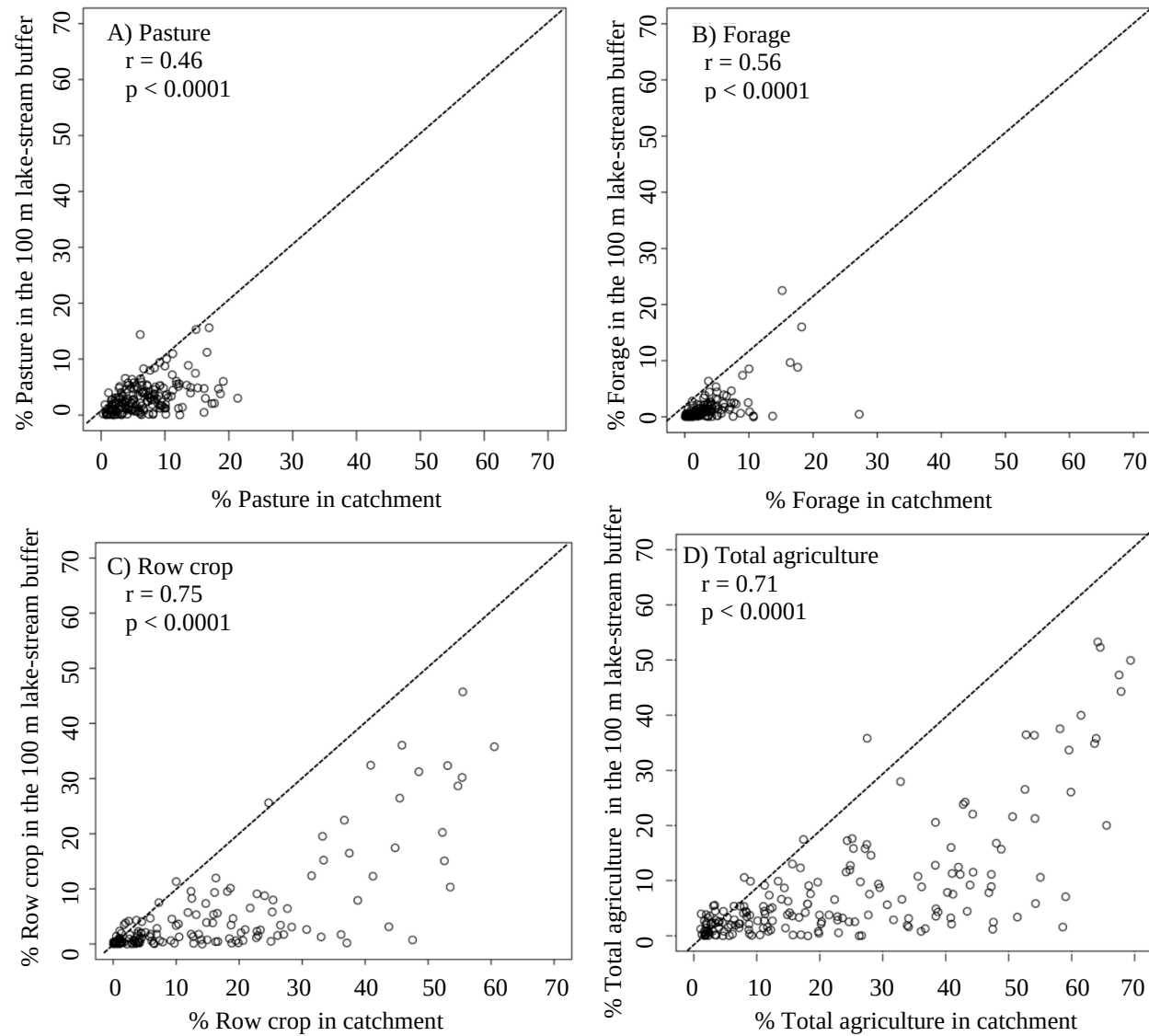


Figure 3. Plots of agriculture measured in the 100 m lake-stream buffer (y axis) versus the catchment for A) pasture B) forage, C) row crop, and D) total agriculture (x axis).

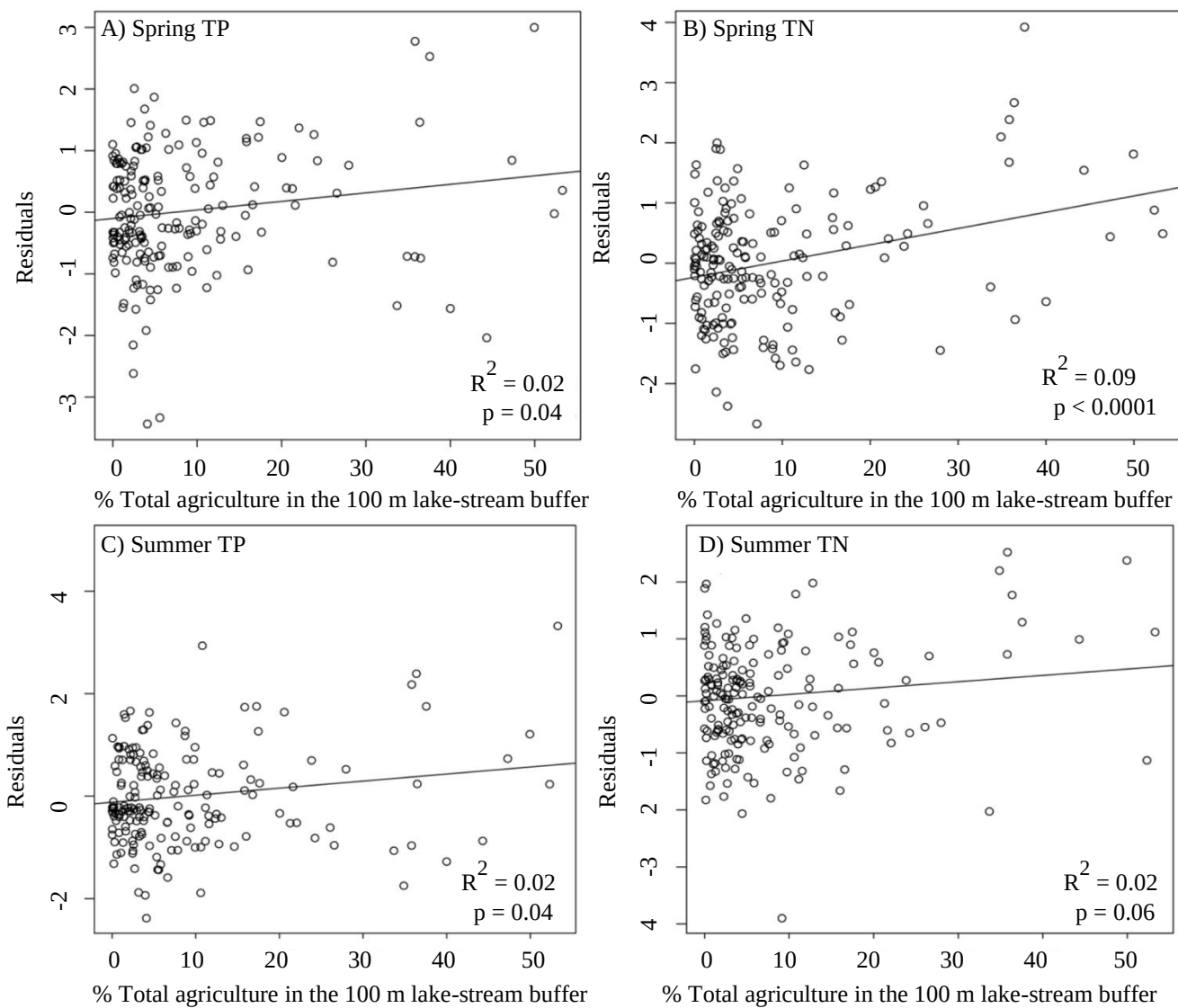


Figure 4. Plots of total agriculture measured in the 100 m lake-stream buffer (y axis) versus the residuals of total agriculture measured in the catchment (x axis) for lake nutrient concentrations.

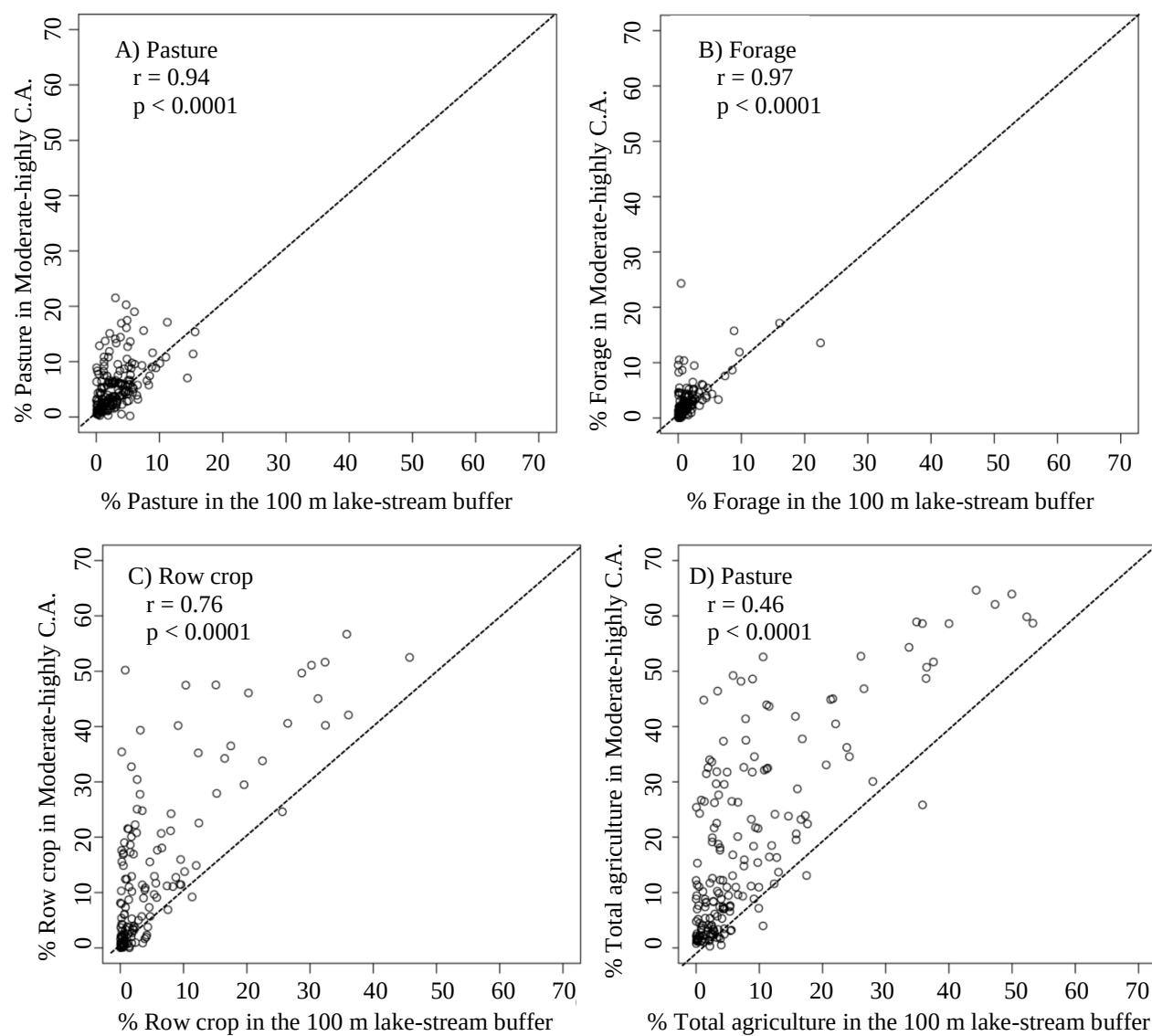


Figure 5. Plots of agriculture measured in the moderate-highly contributing area (y axis) versus the 100 m lake-stream buffer for A) pasture, B) forage, C) row crop, and D) total agriculture (x axis). ‘C.A.’ is contributing area.

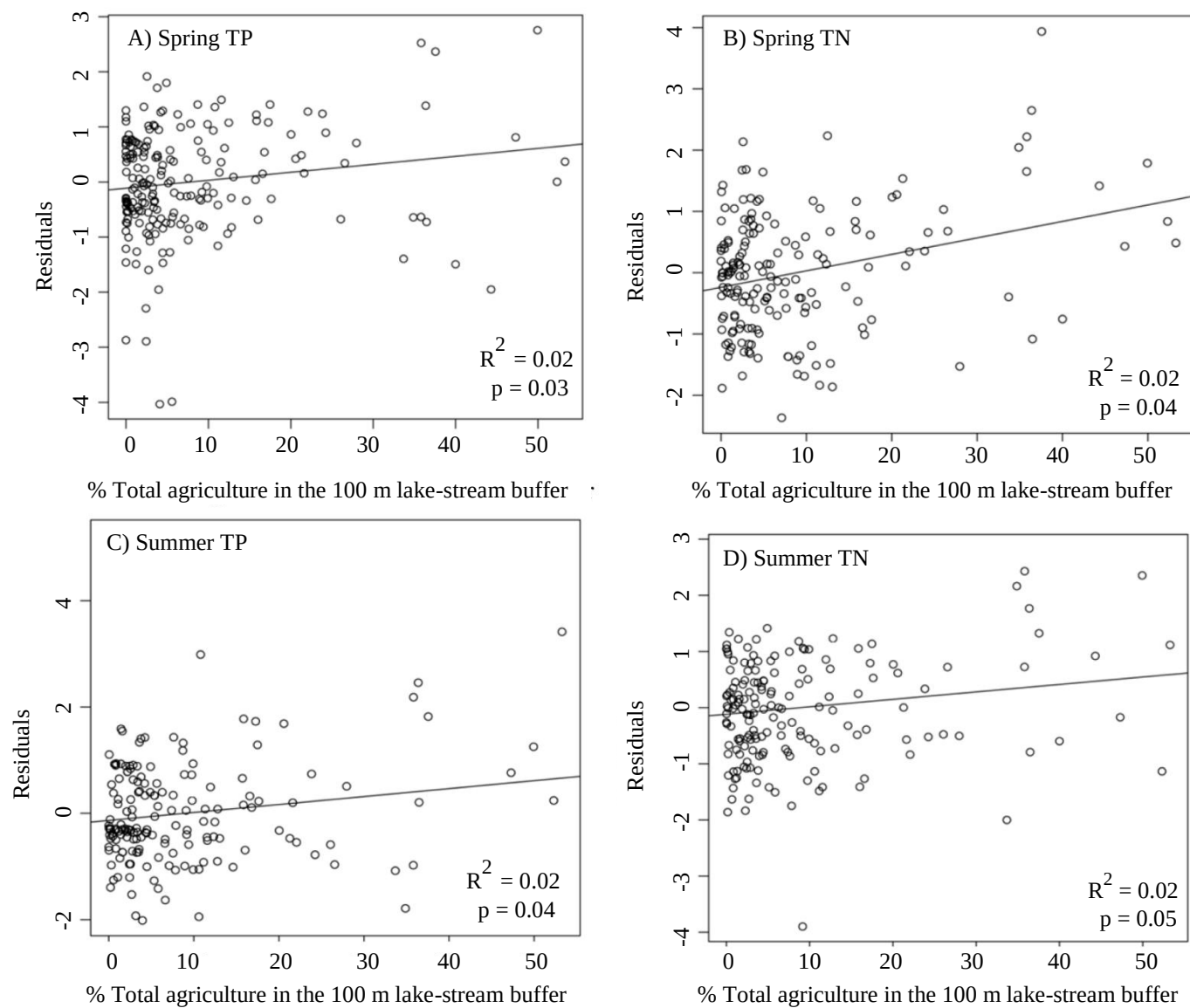


Figure 6. Plots of total agriculture measured in the 100 m lake-stream buffer (y axis) versus the residuals of total agriculture measured in the moderate-highly contributing area (x axis) for lake nutrient concentrations.

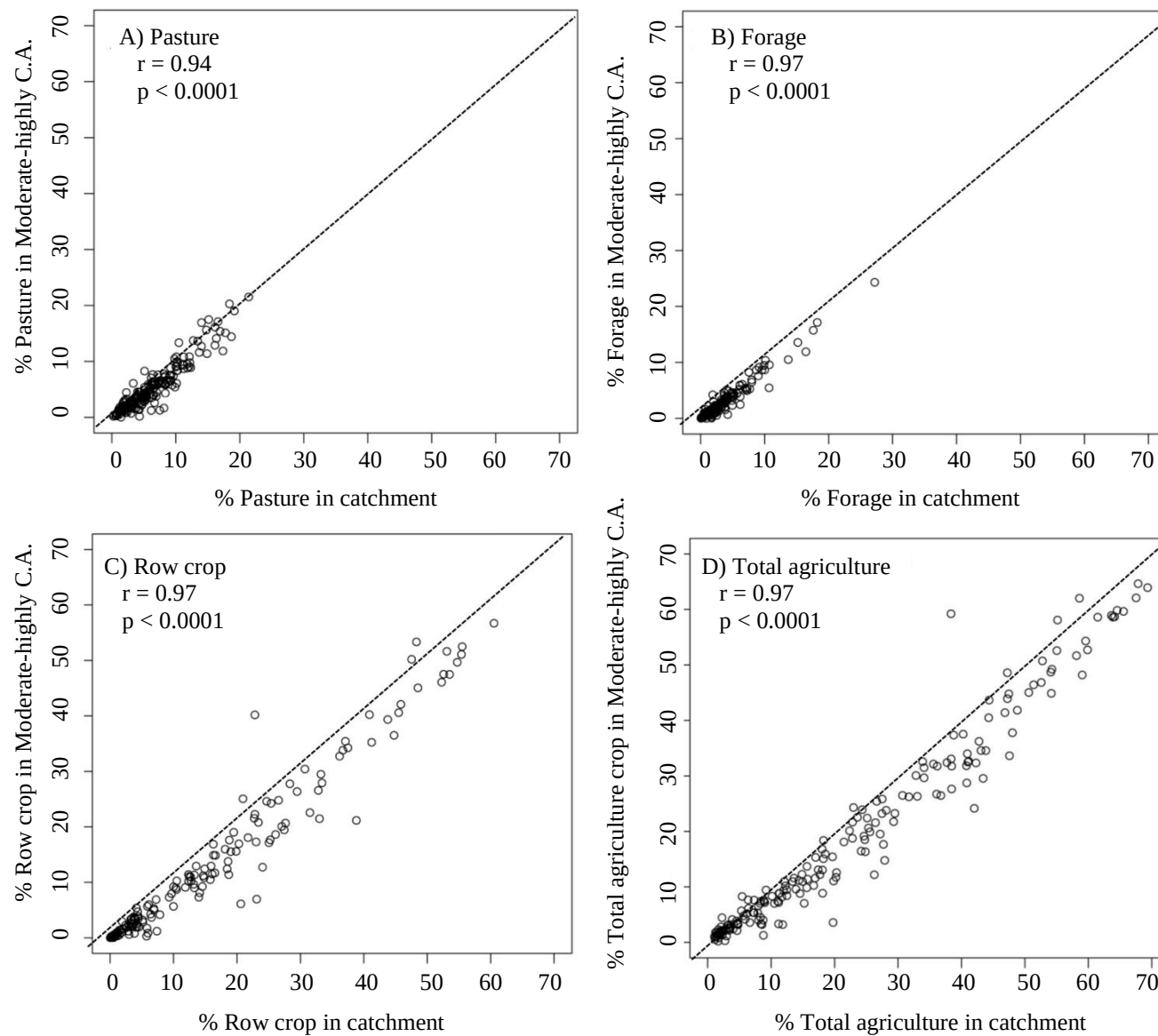


Figure 7. Plots of agriculture measured in the moderate-highly contributing area (y axis) versus the catchment for A) pasture, B) forage, C) row crop and D) total agriculture (x axis). 'C.A.' is contributing area.

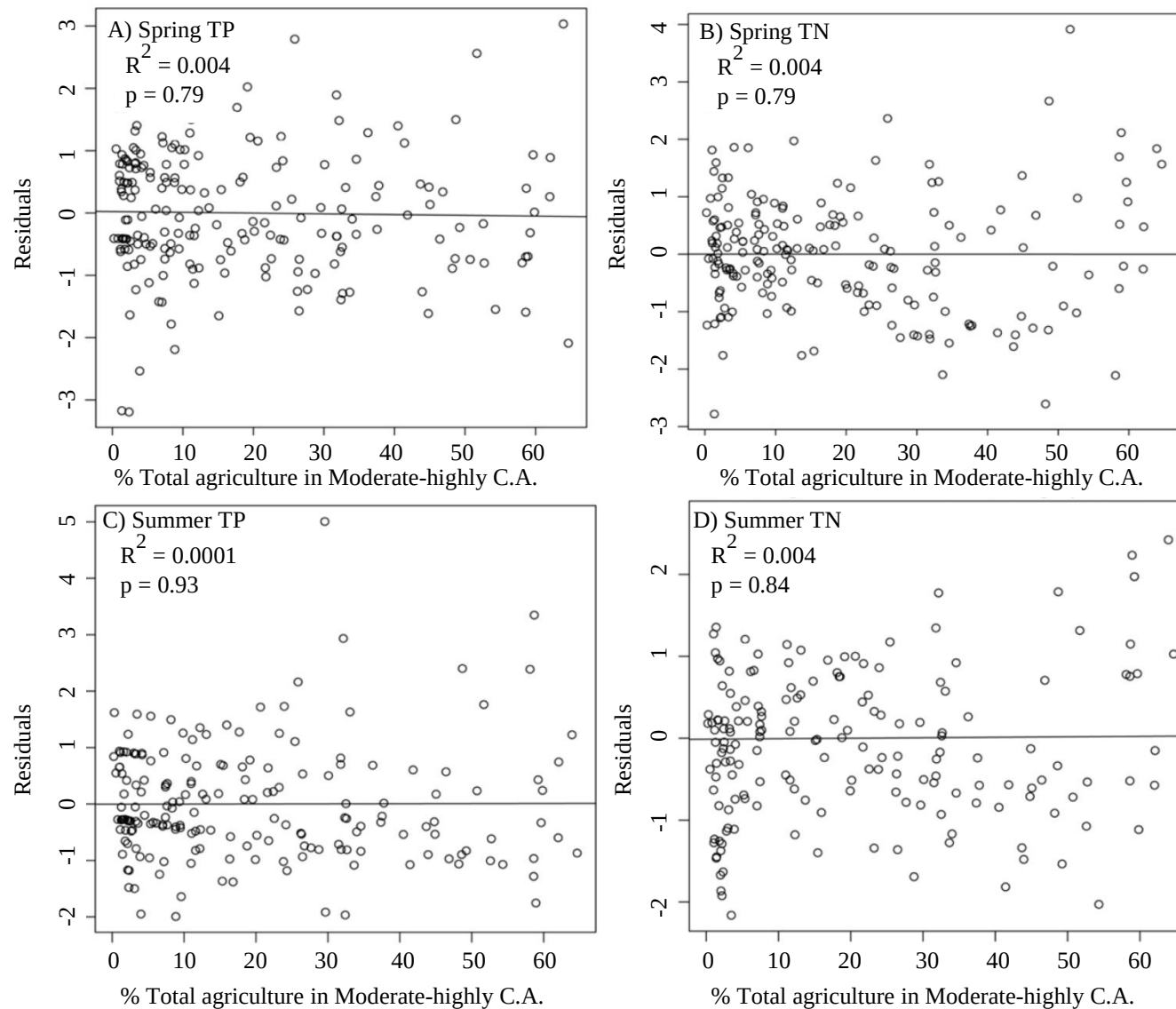


Figure 8. Plots of total agriculture measured in the moderate-highly contributing area (y axis) versus the residuals of total agriculture measured in the catchment (x axis) for lake nutrient concentrations. 'C.A.' is contributing area.

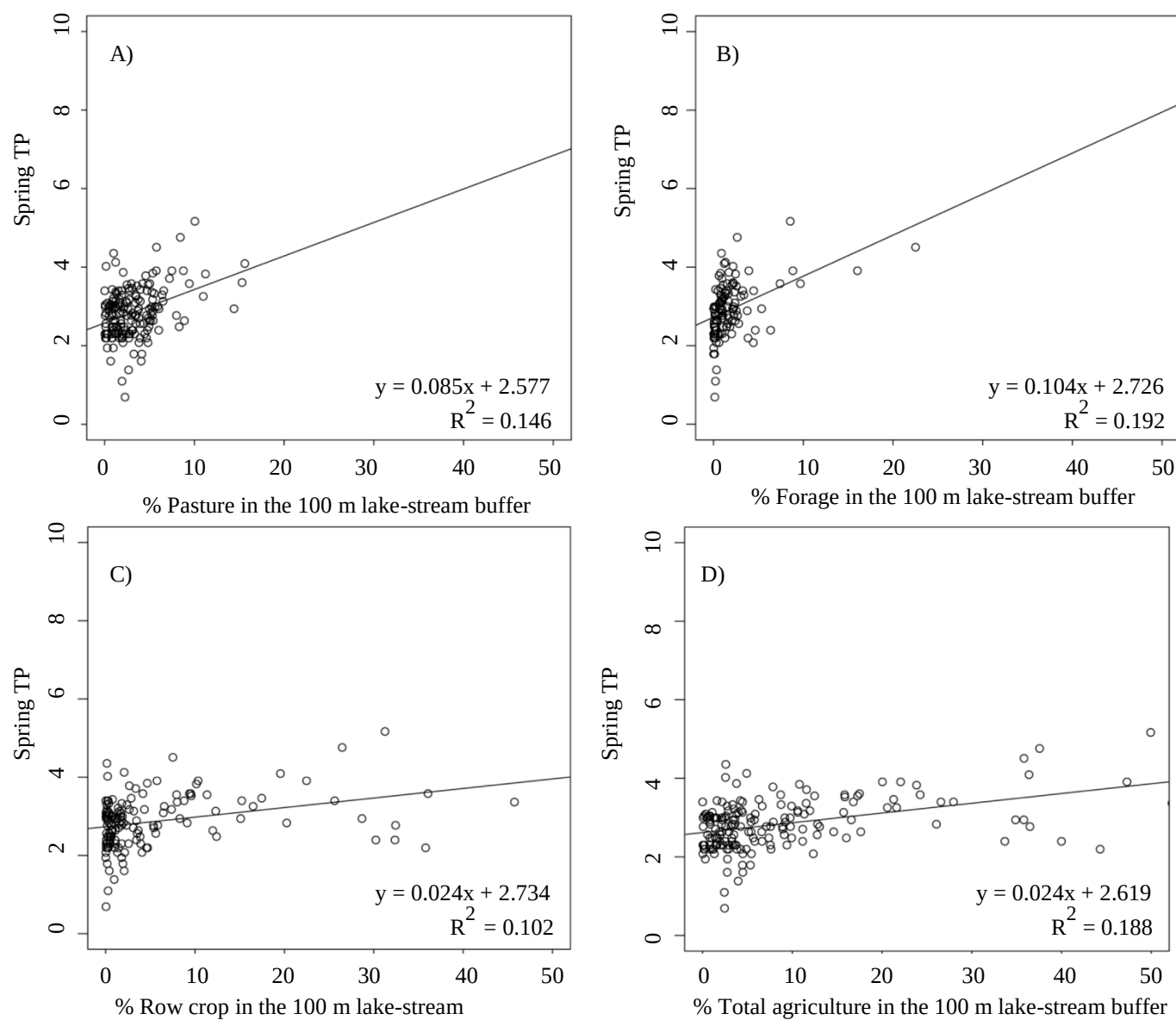


Figure 9. Linear regressions of spring TP (y axis) versus percent agricultural type measured in the 100m lake-stream buffer for A) pasture, B) forage, C) row crop and D) total agriculture (x axis).

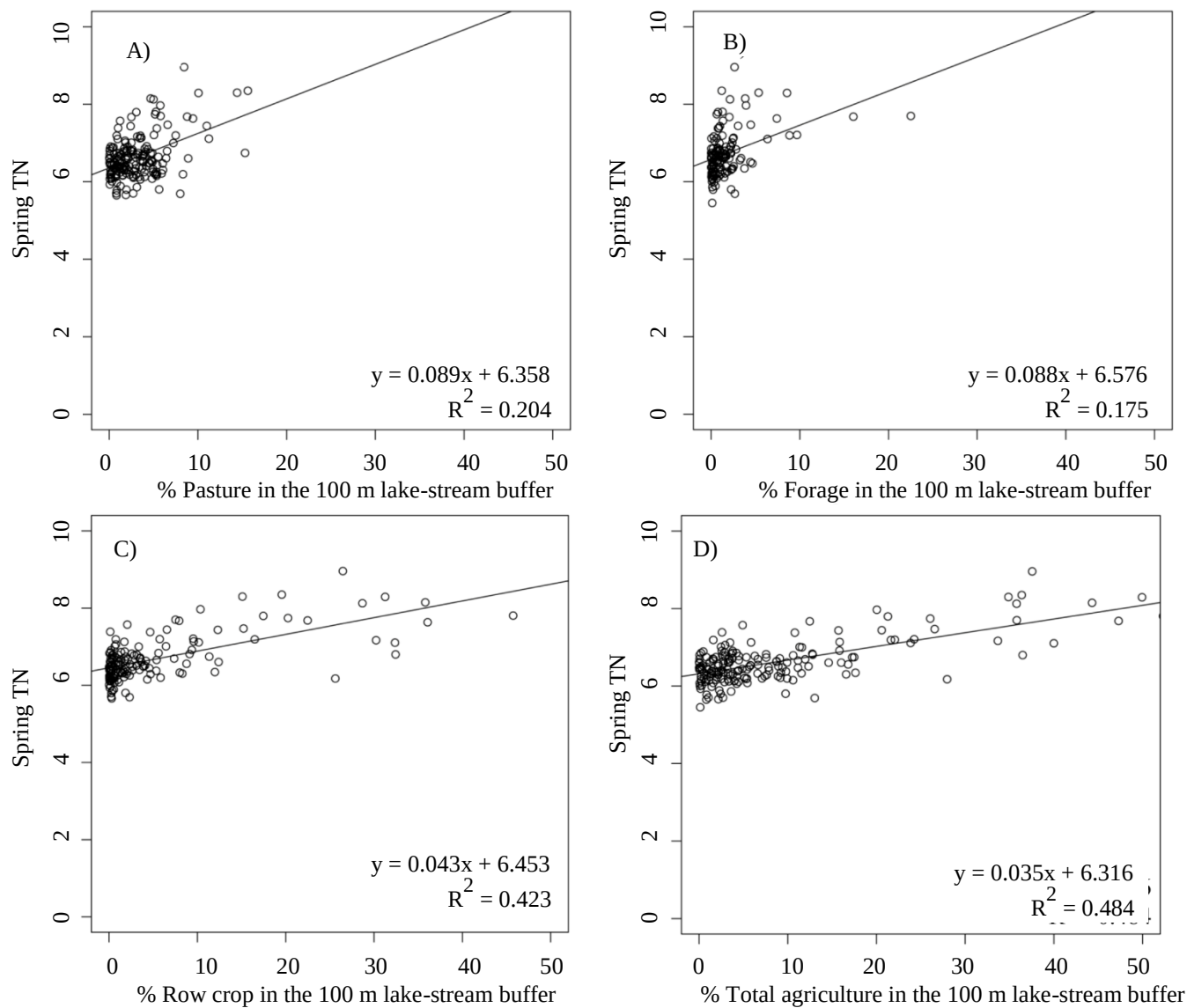


Figure 10. Linear regressions of spring TN (y axis) versus percent agricultural type measured in the 100 m lake-stream buffer for A) pasture, B) forage, C) row crop and D) total agriculture (x axis).

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