Lake Water Quality in Maine's Changing Landscape

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Abstract

This research focuses on the interactions between land-use and lake water quality and strives to provide scientific research to support practical management decisions. Maine, a lake-rich state with nearly 1 million acres of lake area, serves as an excellent study area to examine these interactions. Two types of empirical modeling are combined to address lake water quality in Maine's changing landscape. A state-wide spatial economic model of conversion of undeveloped land to developed land is estimated using 30m resolution land-cover data. Binary logit results find positive and significant correlations between such conversions and neighboring development as well as proximity to the coast, the City of Portland, lakes, and major roads. Agricultural land is more likely to be converted than other undeveloped lands. In rural areas, positive and significant correlations are also found between conversions and proximity to rivers, minor roads, and service centers. A basic empirical model of total phosphorus (TP) is estimated to represent one dimension of lake water quality. Linear regression analysis of data describing 531 Maine lakes reveals significant and positive correlations between TP and catchment to lake area ratio as well as the percentages of land in developed and wetland cover within a 500m buffer of the lake. Negative and significant correlations are found between TP and lake depth and retention time. The results of the two models are combined to simulate future land cover and TP levels. This pilot research illustrates the utility of interdisciplinary land-use science research.

Keywords: lake management, land-use change, phosphorus, spatial analysis, water quality

Introduction

Lakes are an important part of Maine’s character and place. Maine’s 5,782 lakes cover nearly a million acres of the state and range up to 74,890 acres in surface area and 316 feet in depth (Maine DEP 2002). Maine lakes contribute significantly to Maine's economy by providing myriad services. These include the provision of recreation and tourism opportunities, the enhancement of property values, the supplementation of drinking water supplies, aesthetic values, and the provision of habitat (Maine DEP 2000; Boyle et al. 1998; Poor et al. 2001; Schuetz et al. 2001; Michael et al. 1996; and Parsons and Hauber 1998). Boyle et al. (1997) suggest Maine's Great Ponds (lakes greater than 10 acres in size) generate nearly 13 million recreation users days each year, generating over $1 billion in economic impact annually (Boyle et al). A recent report by the Brookings Institution (Brookings Institution Metropolitan Policy Program 2006) bolsters these conclusions, linking the protection of Maine’s quality of place and natural environment to the achievement of future economic growth.

Similar to policy settings in other states in the U.S., management of non-point source pollution has gained increased prominence in Maine, as managers recognize the growing contribution from this source and comply with the total maximum daily load (TMDL) program (NRC 2001). Changes in land cover and land use can change nutrient runoff. Of greatest concern are those changes resulting in increased eutrophication and decreased water clarity. Excess phosphorus and nitrogen can result in a range of ecological impacts, including toxic algal blooms, fish kills, loss of biodiversity, and loss of aquatic plant beds (Carpenter et al. 1998). Reductions in water clarity have also been linked with reduced enjoyment of Maine lakes by humans (Boyle et al. 1999; Maine DEP 2000; Poor et al. 2001).

A recent assessment of Maine water quality affirms the significance of these effects in Maine.

> "The major threat to maintaining the present lake water quality is changing land use. The greatest change has been the transition from mostly forested land to numerous small residential developments (Maine DEP 1997, p. 18)."

Not only can the conversion of land use from forest to urban increase nutrient loads, but new activities on these residential lands can supply nutrients loads as well. For example, lawn and garden fertilizers, faulty septic systems, washing in or near the lake, and soil erosion can contribute to eutrophication (Carpenter et al. 1998). Lakes have consistently played a prominent role in the spatial distribution and intensity of seasonal residential development in Maine (Hasbrouk 1995). Recent increases in seasonal development and conversion of seasonal to year-round homes have sparked concerns regarding the management of lakeshore development and the impacts of such development on water clarity and other lake services.

This research focuses on the interactions between land-use and lake water quality. Maine, a lake-rich state, serves as an excellent study area to examine these interactions. Two types of empirical modeling are combined to address lake water quality in Maine's changing landscape. First, a state-wide spatial economic model of conversion of undeveloped land to developed land is estimated using 30m resolution land-cover data. A binary logit model of such conversions is developed to assess potential drivers of land-cover change. In developing this model, we draw from recent economics studies focused on spatial modeling of land use and land-cover change as well as previous economic work conducted in Maine (see Plantinga and Irwin (2006) for a recent review of these empirical models; Bockstael 1996; Plantinga et al. 1997).

Second, a basic, empirical limnological model of total phosphorus (TP) is estimated to represent one dimension of lake water quality. A linear regression model is developed to describe the variation in TP across 531 Maine lakes as a function of lake characteristics as well as the composition of land cover in the lake's watershed as well as in a 500m buffer around the lake. In developing this model, we draw extensively from ongoing research examining these interactions in Maine and 3 other lake-rich states of the U.S. (Webster et al. 2007) as well as other relevant empirical research (Soranno et al. 1996; Tong and Chen 2002; Atasoy et al. 2006; Arbuckle and Downing 2001; Pettersson 1998; Chambers et al. 2006).

The results of the two models are combined by employing forecasts of future land cover to forecast future TP levels. This process enables the simulation of future development patterns and lake water quality. Emphasis is given to the sensitivity of the distribution of lakes by TP class to future increases in the developed land cover of Maine's landscape. This paper summarizes the state of ongoing research and serves as an example of interdisciplinary land-use science. This pilot research is the first output of an interdisciplinary project funded by US EPA to examine the social and ecological ramifications of landscape change on Maine's lake ecosystems. Because Maine is not as developed as other lake-rich states, we are hopeful that this and subsequent research completed as part of the interdisciplinary project have the capacity to support future management decisions that will support a sustainable form of lake management.

Data

We begin with a brief review of our data sources. Spatial data are used extensively in this analysis. Land cover data, employed in the economic and limnological models, are drawn from the 1992 and 2001 Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Data for Maine. Few classified raster spatial datasets available for Maine include the full range of land cover classes (e.g., urban or developed, forest, agricultural, and wetland). Although tremendous attention has been given to transitions among forest classes, no studies have completed state-scale analysis of land cover transitions with an emphasis on developed land use. The two NLCD 30-meter resolution raster data layers were retrieved from the USGS website and reprojected to UTM Zone 19 North to match the convention of the Maine Office of GIS. Different land cover classification methods were used to create the NLCD data in 1992 and 2001. We recognize the problems associated with this but lack any reliable substitute land cover data at this time[1]. Reclassification was done to aggregate the individual cover classes into 5 categories: developed; forest; agriculture; wetland; and other[2]. This aggregation may lessen some of the problems caused by the distinct classification methods. The 1992 data layer was used to establish a base raster including data on over 200 million 30 m by 30 m grid cells. Figure 1 displays the distribution of cells by these five classes based on the 1992 and 2001 NLCD data. Several important features of Maine's landscape are revealed by these figures. Maine's landscape is largely in forest cover (over 70 percent of the classified cells). These cover data show very modest changes over this time period, with slight reductions in cells classified as forest and other cover and slight increases in cells classified as developed and wetland. The increase in the developed cells is the focus of the land-cover change modeling discussed in a later section of this paper.

Several spatial data layers were obtained from the Maine Office of GIS. These layers include areas with elevation above 2700 feet (MECON2700 data layer) and conservation lands (MECNSLAND). Data describing Maine lands falling in the National Wetland Inventory and the location of Maine lakes and rivers were obtained from the Maine Department of Environmental Protection (Michael Smith, personal communication). Data describing Maine's road network were obtained from the Maine Department of Transportation. Spatial data describing regional service centers and Maine's coastline were created as part of this project. Figure 2 displays some key features of Maine's landscape, including the spatial distribution of its lakes (in blue) and conservation lands (green). The City of Portland, its only major urban area, is shaded in red and located in the southern portion of the state.

The bulk of the data used in the analysis of total phosphorus (TP) in Maine lakes were compiled as part of a multi-institutional lake classification project funded by US EPA (Soranno, Webster, Bremigan, and Cheruvelil served as PIs of that grant; see Webster et al. 2007 for more details). The water quality data were collected by the Maine Department of Environmental Protection and were subject to quality review. Variables used in this analysis include TP, lake depth, lake area, catchment (watershed) area, and water retention time. All lakes in this sample had a minimum surface area of 10,000 square meters and a minimum depth of 2 meters. Measurements were done on a single sampling date in late summer for each lake to allow coincident measurements of TP, color, chlorophyll and Secchi transparency. The Maine samples were collected in the late summer between 1996 and 2003. The final sample includes TP readings from 531 lakes. This sample is not a random sample and was chosen based on the mentioned size constraints as well as data availability across several water quality measures.

Watersheds were delineated using USGS HUC 8 designations. This resulted in 21 HUC (Hydrologic Unit Code) 8 units in the State of Maine. Although not all HUC 8 units are true watersheds, these units do represent the USGS' nested series of hydrologic units. A spatial data coverage of the HUC 8 units was obtained from the University of Maine Senator George J. Mitchell Center for Environmental and Watershed Research.

Land Cover Change Model

The land cover change model focuses on the conversion of undeveloped land cover classes (forest, agriculture, wetland, and other) to developed land cover classes from 1992 to 2001. Some undeveloped lands were excluded from this analysis, as they are not permitted to be developed (conservation lands and National Wetland Inventory lands). Of the approximately

67.5 million undeveloped grid cells that could have been developed, approximately 2.5 million grid cells transitioned from an undeveloped to a developed land cover class from 1992 to 2001. The final sample used in the land-cover change modeling includes these cells that were converted and a random set of approximately 11 million controls drawn from the population of "developable" undeveloped cells. Sampling was done using ESRI Arc Info Grid commands, with a goal of having about 4 controls for each converted cell.[3]

Land-cover change modeling was implemented using 2 empirical models corresponding to different regions of Maine (see Figure 2). Region 1 includes southern and mid/lower coast Maine (York, Cumberland, Sagadahoc, Lincoln, Knox, Waldo, Kennebec, and Androscoggin Counties). This region is experiencing population and housing growth and may be characterized as sprawling. Region 2 includes western, downeast, and northern Maine (Penobscot, Piscataquis, Aroostook, Oxford, Hancock, Washington, Somerset, and Franklin Counties). Although this region is experiencing housing growth, some counties within the region lost population from 1990 and 2000 and are continuing to experience such decreases. Region 2 includes more rural areas, with greater reliance on natural resource extraction-based industries and diverse natural amenities, appealing to seasonal home-owners. We expect these regions to capture distinct real-estate markets. By applying separate models to these two regions, we allow for variables to have distinct influences on the likelihood of conversion.

The land-cover change model is estimated as a binary logit model, where the probability of conversion to a developed land cover class (Pr(CONV)) is modeled as a function of numerous independent variables (x), such that

$$\Pr(CONV = 1 \mid x) = \frac{e^{x'\beta}}{1 + e^{x'\beta}} = F(x'\beta)\,.$$

β is a vector of parameters to be estimated, and the notation F( ) represents the cumulative distribution function of the logistic distribution. The economic intuition underlying this simple model is as follows - conversion is more likely in areas where the return to developed use is higher than the return to an undeveloped use. This intuition is consistent with previous economic studies of land use and land cover change (Bockstael 1996; Bockstael and Bell 1998; Plantinga et al. 1997). Because the return to developed uses swamps that of undeveloped uses in Maine (e.g., forest and agriculture), considerable emphasis is given to including independent variables (x) that capture variation in expected returns in residential use and represent the returns to converting undeveloped to developed land. Developed lands in Maine are largely residential areas.

Figure 3 displays the cells that converted to developed use from 1992 to 2001 shaded in red. Cells shaded in red correspond with dependent variables equal to 1 in the binary logit models. Conversions are more intensely distributed in the southern portion of the state and cluster near road networks. Few conversions occur in the northwest portion of the state.

Tables 1 and 2 respectively present the variable names and descriptions and descriptive statistics for the dependent and independent variables employed in the land-cover change model. The dummy variable representing an initial cover of agriculture (AG1992) is included to distinguish the lower costs of conversion from undeveloped to developed use relative to cells with forest cover. It is expected to have a positive influence on conversion. The percentage of cells in a developed land cover class in 1992 within a 7 by 7 rectangular neighborhood (of cells) (NDEV) is used as a measure of the intensity of existing development. Because this variable may pick up the presence of existing infrastructure (and therefore lower costs of conversion), it is expected to have a positive influence.

Numerous distance measures are included in the model, capturing the variation in proximity to various amenities, including mountain views (LNHELEV), the Maine coastline (LNCOAST), the City of Portland (LNPORTLAND), rivers (LNRIVER), lakes (LNLAKE), and major roads (LNMAJRD). Because of the expected positive contribution of these amenities to returns in residential use, a greater distance (less proximity) is expected to have a negative influence. Distance terms are included as natural logarithms to allow for nonlinear effects of proximity on the probability of conversion. Likewise, proximity to minor roads (MNRD10K) and regional service centers (SERV10K) are also expected to be amenities and therefore have a positive influence on the probability of conversion to a developed land cover class. These latter variables are measured as binary dummy variables to avoid high correlation with other independent variables.

Total Phosphorus Model

The development of the total phosphorus model closely follows ongoing research examining these interactions in Maine, New Hampshire, Michigan, and Wisconsin by Webster et al. (2007). Webster et al. (2007) examines total phosphorus (TP) and color to quantitatively analyze the nutrient-color paradigm for defining lake trophic status. They find color and TP influence both chlorophyll and Secchi transparency. Webster et al. (2007) also explored variation in TP using multiple regression analysis. A negative and significant ($p<0.001$) correlation is found between maximum depth and TP. A positive and significant relationship ($p<0.05$) is found between the ratio of catchment area to lake area. Negative and significant correlations are determined between the percentages of forest ($p<0.001$) and wetland ($p<0.05$) land cover (NLCD1992) in a 500 m lake buffer.

This analysis follows the modeling of Webster et al. (2007) closely, with two exceptions. First, this empirical model only addresses Maine lakes ($n=531$). Second, this analysis incorporates land cover information at two scales - watershed-scale and a 500 m buffer-scale. The second extension permits multiple types of interactions between landscape cover and water quality. Furthermore, it allows for more extensive feedbacks with the land-cover change model. Figure 4 displays the 531 lakes included in the sample and summarizes the spatial variation in TP across these lakes. The shading of the thematic map distinguishes lakes by TP class. The sample is grouped as follows: ultra-oligotrophic (80 lakes; 15% of the sample; TP < 5 ppb); oligotrophic (291 lakes; 55% of the sample; TP 5-10 ppb); mesotrophic (153 lakes; 29% of the sample; TP >10 - 30 ppb); and eutrophic (7 lakes; 10% of the sample; TP > 30 ppb). Red and green shading indicates higher levels of TP.

Table 3 presents the variable names, descriptions, and descriptive statistics. Based on the recent research of Webster et al. (2007), a negative relationship is expected between TP and maximum depth (DEPTH). Likewise, a positive relationship is expected between TP and the ratio of catchment area to lake area (CTOL).

The percentage of lands falling into our four cover classes of interest (DEVELOPED, FOREST, WETLAND, and AGRICULTURE) are calculated for each lake at the catchment (watershed; HUC8) scale (W_DEV; W_FOREST; W_WETLAND; and W_AG) and within a 500 m lake buffer (B_DEV; B_FOREST; B_WETLAND; and B_AG). Figure 5 reveals the variation in land cover composition across HUC 8 areas in Maine. There are 21 HUC 8s, or watersheds, in Maine. The watersheds range from .057% (Allagash Watershed) to 13.44% (Presumpscot Watershed) developed land cover. The percent of developed land, as seen in Figure 5, differs greatly between the northern Maine, with low percentages of development, and southern Maine, with higher percentages of development. The percent of forest cover follows the opposite pattern between Northern and Southern Maine. The percentages for forest cover range from 61.78% in Presumpscot Watershed (Southern Maine) to 89.60% in Allagash Watershed (Northern Maine). All 21 watersheds have the majority of their land cover in forest cover. The percentage of agriculture land cover ranges from zero percent in Upper

Androscoggin to 18.52% in Meduxnekeag. The percentage of wetland land cover ranges from 4.77% in Upper Androscoggin to 15.93% in Mattawamkeag watershed (Figure 5). Figure 6, which displays the 2002 NLCD land cover data along with the boundaries of the 2 areas over which cover statistics are calculated, shows an example of the difference in scale of a watershed (black outline) and 500 m buffer (gray outline).

Priors of the relationships between these variables and TP are mixed. Percentage developed land cover (W_DEV and B_DEV) is expected to have a positive influence on TP at both scales because of the impact of impervious surfaces on delivery to lakes as well as increased TP loads due to human activities. Similar expectations hold for percentage of agricultural land cover (W_AG and B_AG). The role of forest and wetland land covers is less clear (W_FOREST; B_FOREST; W_WETLAND; B_WETLAND). Forest lands export far less TP than developed and wetland land covers and therefore may have a negative influence on TP at the watershed and buffer scale. The role of wetland land cover is uncertain, as there is variation in these lands acting as sources or sinks of TP. Correlation among this set of independent variables guides us to employ only a subset of the land cover measures in the final analysis. Developed and wetland land covers were not found to be highly correlated, and the measures (W_DEV; W_WETLAND; B_DEV; B_WETLAND) corresponding with these two cover classes are employed in the empirical TP model. Interpretation of the influence of these land cover variables is complicated by the correlation across land cover classes.

Results

Table 4 summarizes the results of the binary logit models of conversion to developed land cover classes. Recall the results cover 2 distinct regions of Maine. The sets of parameters were estimated by maximum likelihood. All estimated parameters are significant ($p < 0.0001$) and generally take the expected sign. Higher levels of surrounding developed land (NDEV) and an initial state of agriculture (AG1992) increase the likelihood of conversion, *ceteris paribus*. Greater distance from Maine's coastline (LNCOAST), Portland (LNPORTLAND), lakes (LNLAKE), and major roads (LNMAJRD) decrease the likelihood of conversion, *ceteris paribus*. Proximity to higher elevated areas (LNHELEV) did not appear to be valued as an amenity, with an unexpected positive sign appearing in both models. Greater distance from a river (LNRIVER) unexpectedly increased the probability of conversion in Region 1 and decreased the probability of conversion in Region 2. This may reflect the relatively higher quality rivers in Region 2 and a lack of available land for development near rivers in Region 1. Proximity to a service center (SERV10K) had a negative influence in Region 1 and a positive influence in Region 2. The positive sign for Region 2 may reflect the greater variation in access to service centers in this region; whereas the negative sign in Region 1 may reflect a desire to locate outside of a service center or a lack of developable land in established service centers in the more urban Region 1.

Results of the regression analysis of the variation in TP are displayed in Table 5. A variety of functional forms were explored (linear, semi-log, double-log). Following convention and statistical tests, a double-log functional form was used. The results for maximum depth (LNDEPTH) and ratio of catchment area to lake area (LNCTOL) match expectations. More shallow lakes have higher TP levels, *ceteris paribus*. Lakes with greater catchment to lake area (CTOL) ratios also have higher TP levels, *ceteris paribus*. The independent variables linked with land cover at the watershed scale are not significant. In contrast, the buffer-scale measures are significant. The positive influence of a higher percentage of developed land cover in a 500m buffer on TP (B_DEV) is consistent with expectations. The positive influence of wetland cover on TP (B_WET) suggests these proximate wetland areas serve as sources of TP. The estimated parameters from the second specification shown in Table 5 is used in the simulation of future TP.

Discussion

The primary purpose of this pilot project was to encourage interdisciplinary modeling and permit the simulation of future land cover and TP levels. The results of the models displayed in Table 4 were used to generate predicted probability of conversion surfaces (see Figure 7) for Regions 1 and Region 2. This was done using ESRI's Arc Info GRID programming. To forecast future land cover, a simulation was done based on these predicted surfaces. The cells employed in the simulation were lands that appeared developable as of 2001. Specifically, these included grid cells in an undeveloped land cover class in 2001 and not conservation or National Wetland Inventory lands. In keeping with the distinction between the 2 regions of Maine, the simulation of a future land cover is based on approximately 1 million future conversions (cells) to developed land cover in Region 1 and 1.4 million cells in Region 2. This simulation attempts to replicate the overall magnitude of change from 1992 and 2001 as well as preserve the relative intensity of change in the two regions. GRID programming is used to order cells according to their predicted probabilities of conversion and to convert cells until the total numbers of cell conversions are met. The final output of this programming is a "future" land cover layer similar in design to the NLCD data layers.

Watershed and buffer scale measures of surrounding land cover based on this one simulated, future land cover were then calculated for all 531 lakes in the TP model sample. This exercise resembles previous work by Bockstael and Bell (1998). Finally, predicted TP levels based on the second set of results shown in Table 5 and these updated land cover measures were estimated[4]. Figure 8 offers one summary of this integrated modeling. Shown in this figure is the actual distribution of lakes by TP class; the predicted distribution of lakes by TP class based on the TP model (Table 5); and the forecasted distribution of lakes by TP class based on the simulation. Note that the model, as might be expected, struggles to predict the tail values and centralizes the distribution of TP values. Nonetheless, comparing the predicted and forecasted values offers a measure of the implications of future conversions of undeveloped to developed land cover on lake water quality in Maine. As shown in Figure 8, overall counts fall in the ultra-oligotrophic and oligotrophic classes, rise in the mesotrophic class, and remain unchanged in the eutrophic class. Reviewing the data, these overall changes in counts represent shifts of 2 lakes from the ulta-oligotrophic to oligotrophic class and 26 lakes from the oligotrophic to mesotrophic class. Such shifts could reflect meaningful changes in the lake ecosystems of Maine.

Conclusions

In this paper, we present an example of interdisciplinary land-use science, combining insights from economics, GIS science, and limnology. These pilot results reflect the progress of an ongoing research project. We are excited by this first round of results and by the opportunities to improve the modeling. Future research will involve re-assessing the use of the NLCD data and exploration of other sources of land-use change data and improving the models of both land-cover change and TP. A related project is examining the utility of parcel-scale land-use data (Atasoy et al. 2006) versus raster land cover and photo data to capture development in rural, lake-rich settings. Unfortunately, consistent parcel-scale data are not available for the State of Maine, as upwards of 400 municipalities track land-use records independently. Other future refinements involve modeling of other water quality measures (e.g., water clarity) and consideration of dynamic modeling to permit feedbacks from human (development) and ecological systems (water quality).

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[1] Characterizing cover changes based on data classified using different methods is complicated as it is unclear whether a change in cover class is a true change or reflects a change in the classification method.

[2] The 1992 NLCD data were reclassed as follows: developed (21, 22, and 23); forest (41,42,43, and 51); agriculture (71,81,82,83, and 84); wetlands (91,92); and other (11, 12, 31, 32, and 33). The 2001 NLCD data were reclassed as follows: developed (21, 22, 23, and 24); forest (41, 42, 43, 51, 52); agriculture (81 and 82); wetland (91, 92, 93, 94, and 95) and other (11, 12, 31, 32, 71).

[3] Ultimately, converted cells in Region 2 were matched by more than 4 controls and converted cells in Region 1 were matched by less than 4 controls. Future work will adjust the selection of controls to fix this problem.

[4] Predictions did address the double log functional form.

Figure 1
Land-Cover Change Model: Comparing NLCD 1992 and NLCD 2001 (State of Maine)

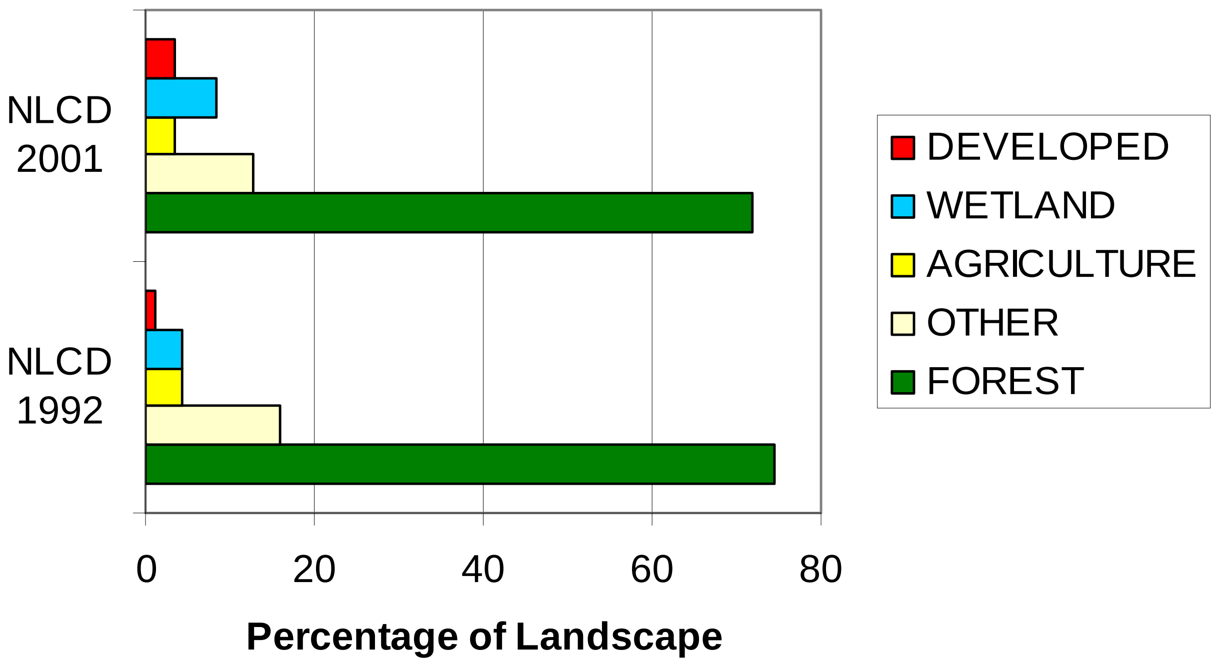

Figure 2
State of Maine: Lakes, Conservation Lands, and City of Portland

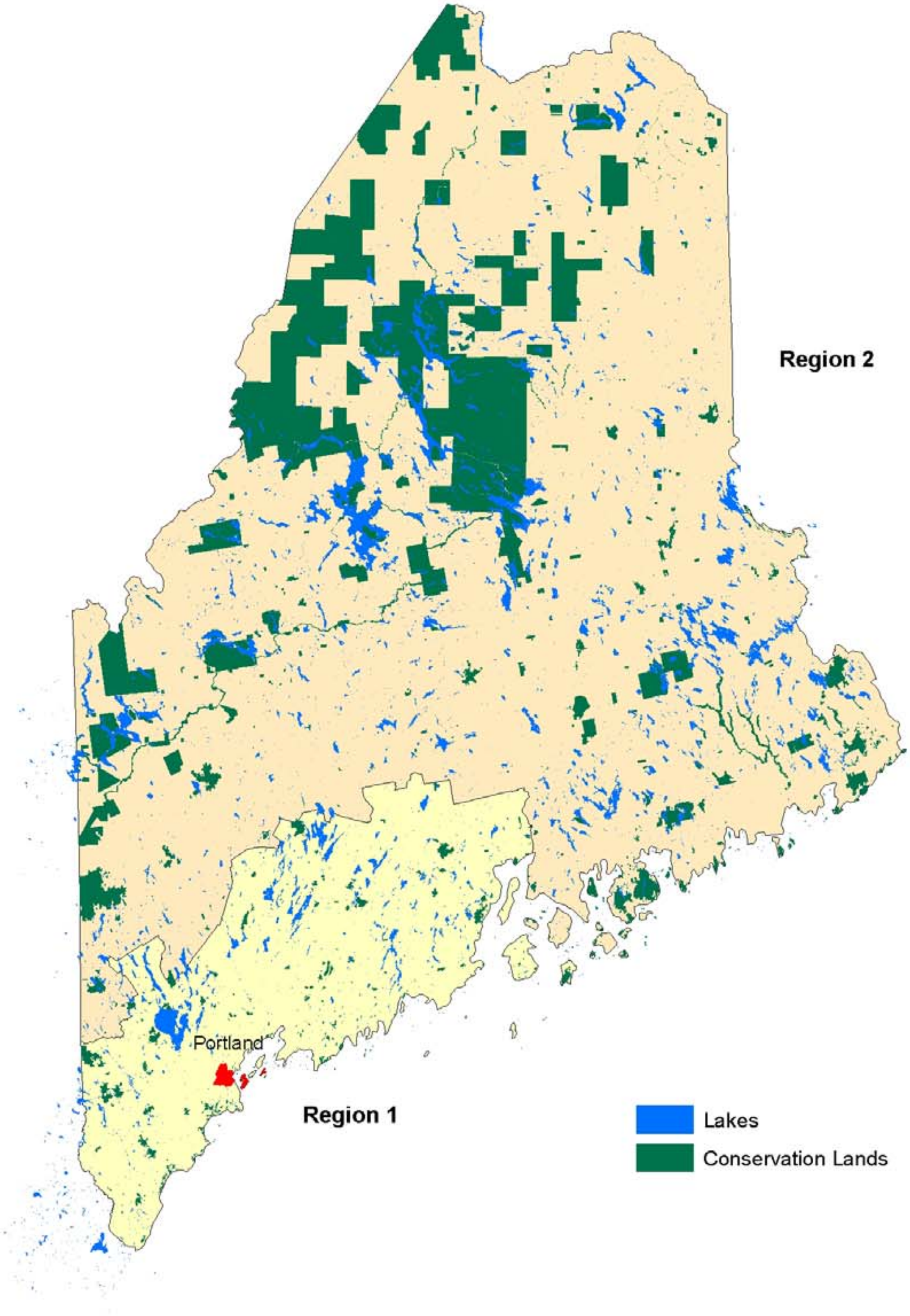

Figure 3
Land-Cover Change Model: Conversions from Undeveloped to Developed Land Cover

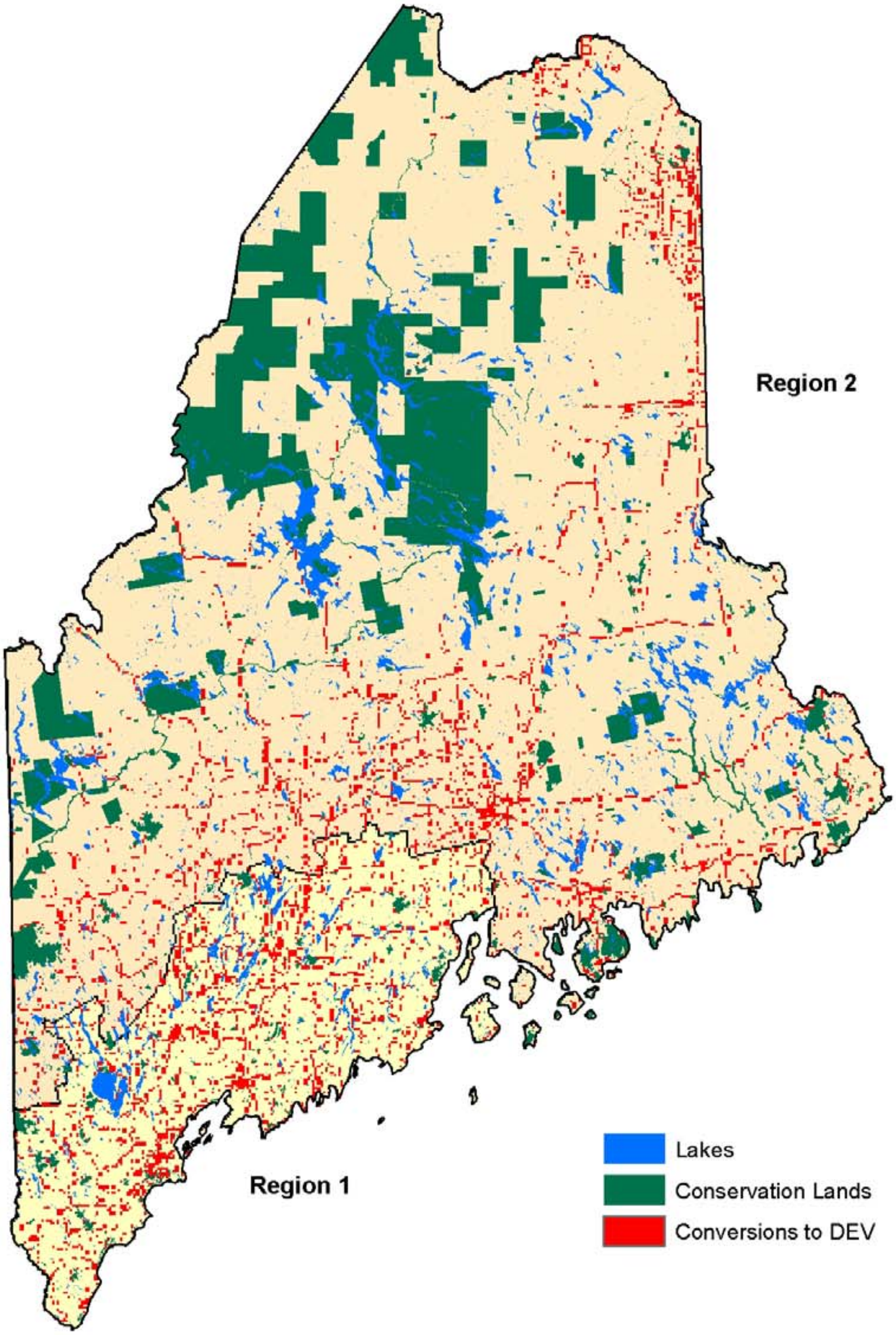

Figure 4
Total Phosphorus (TP) Model: Lakes by TP Class (n=531)

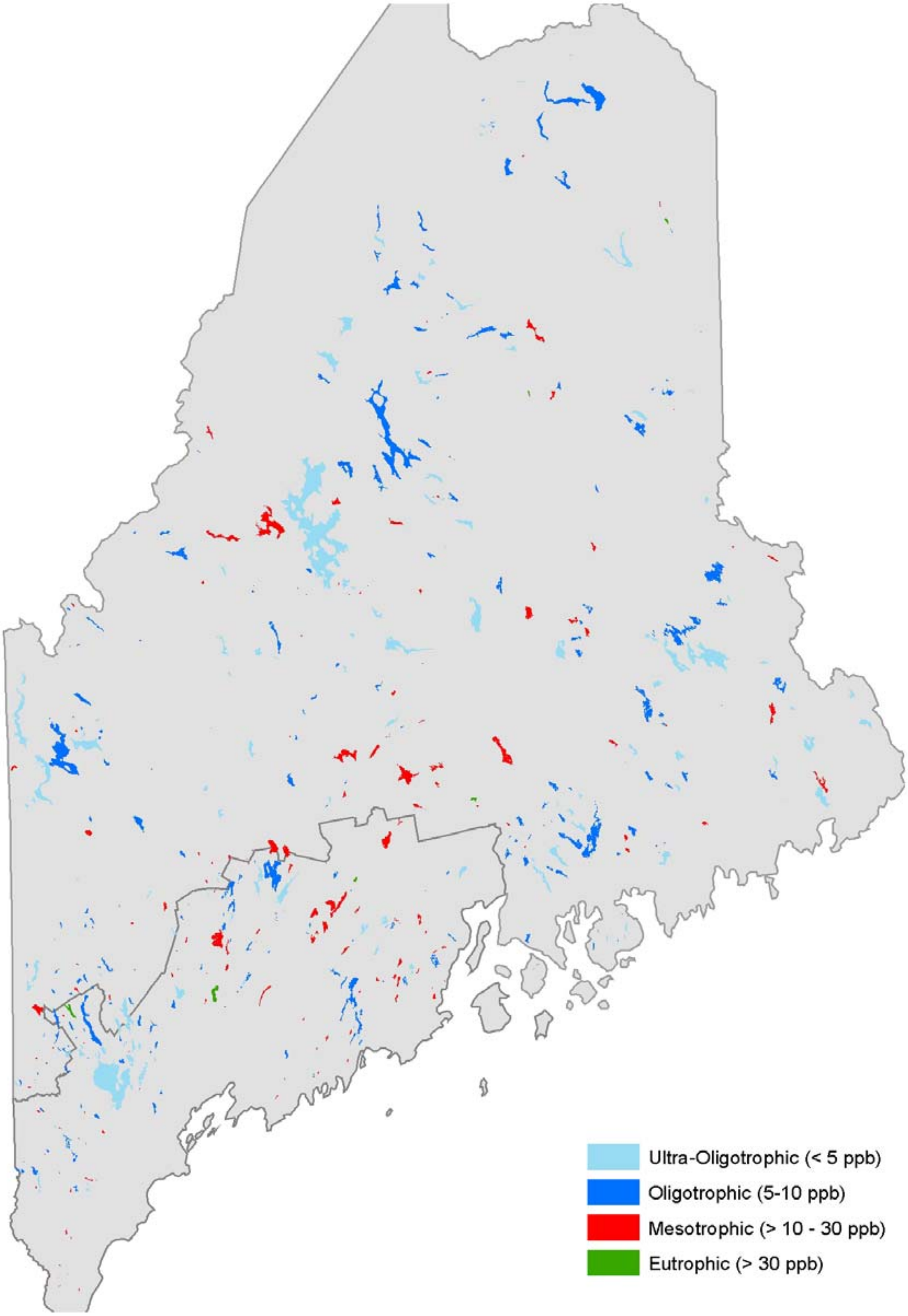

Figure 5
Total Phosphorus (TP) Model: Watershed-Scale Land Cover Measures

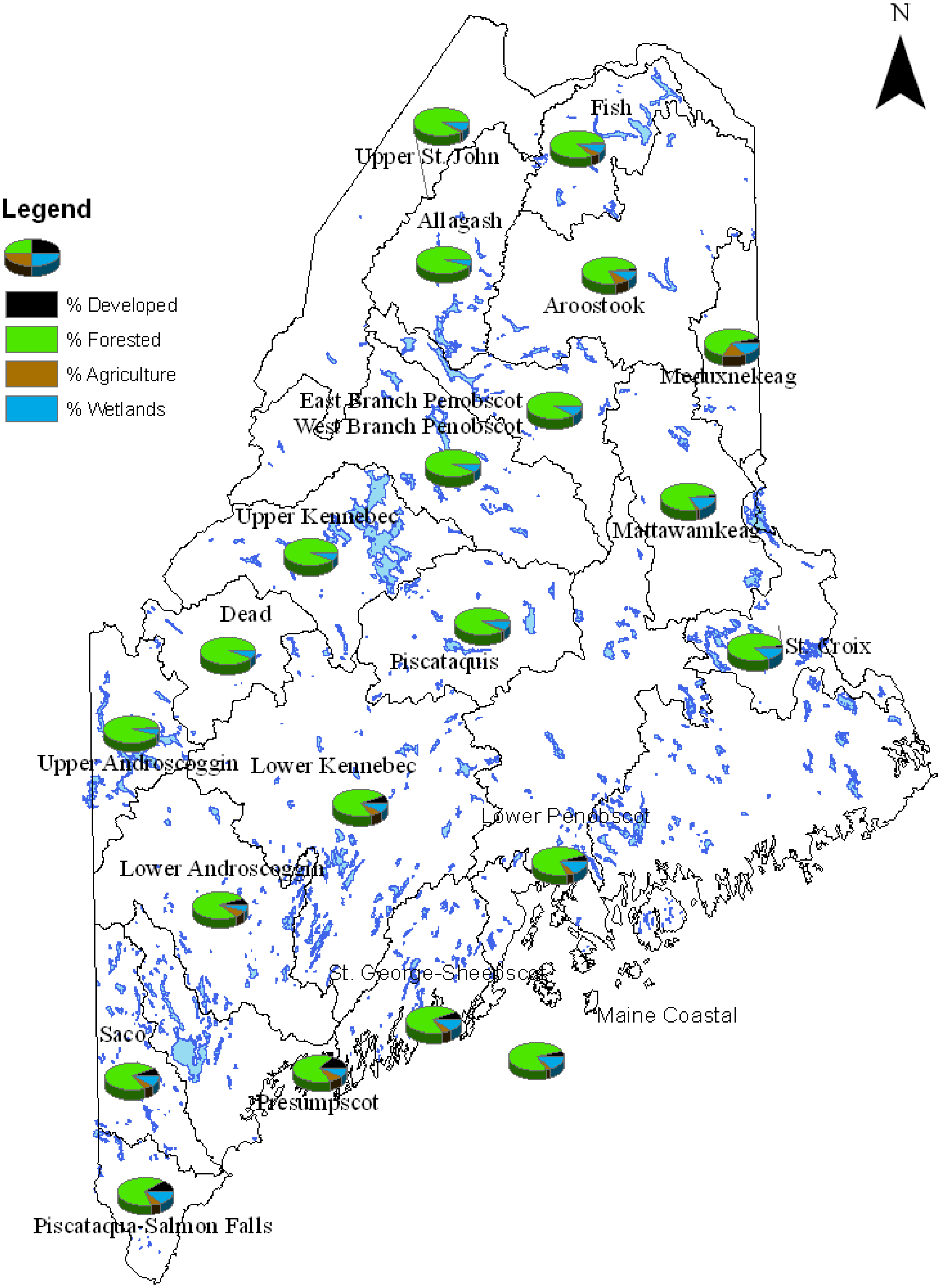

Figure 6.
Total Phosphorus Model: Watershed- (black) and 500 m Lake Buffer- (Gray) Scale Land Cover Measures

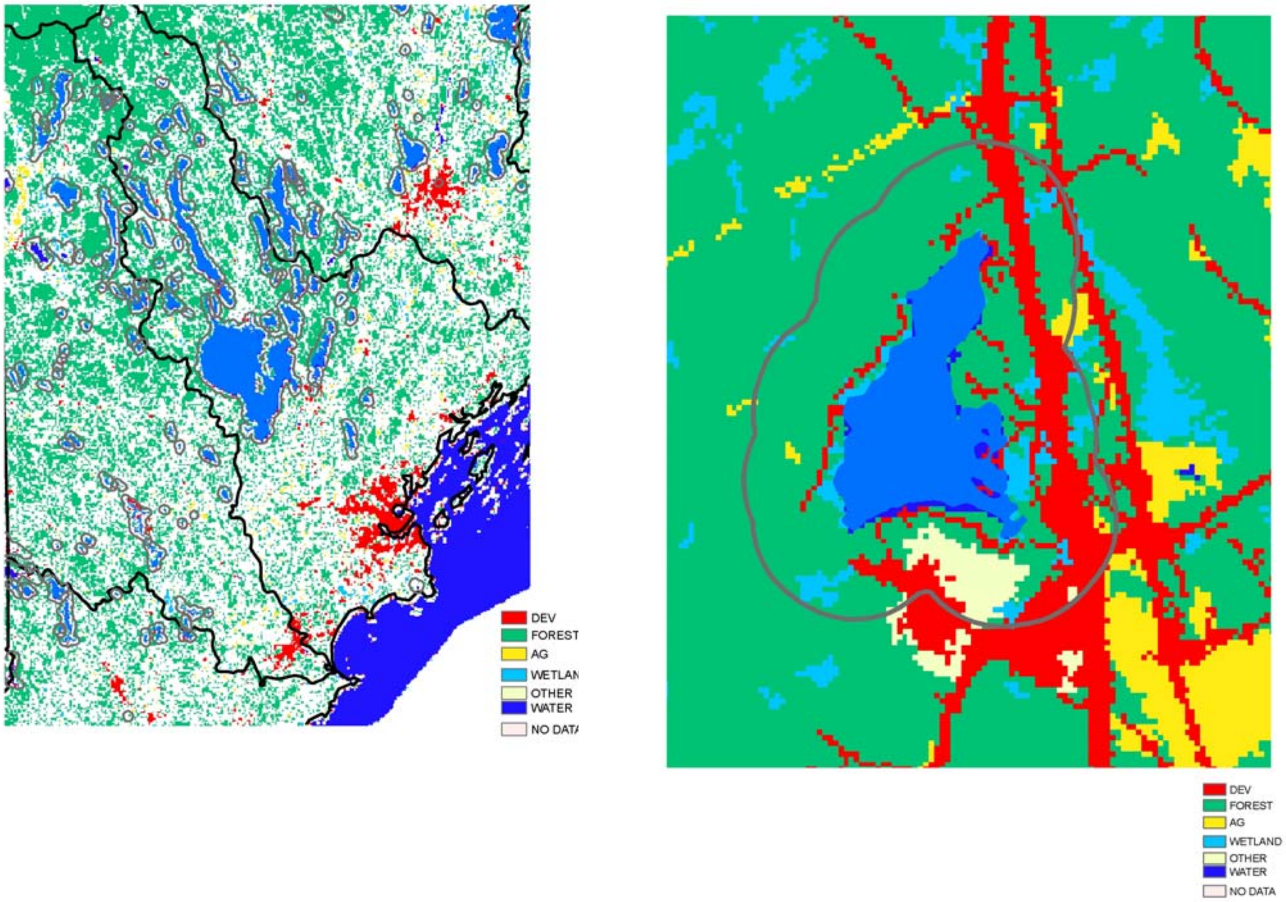

Figure 7.
Land-Cover Change Model: Predicted Probability of Conversion

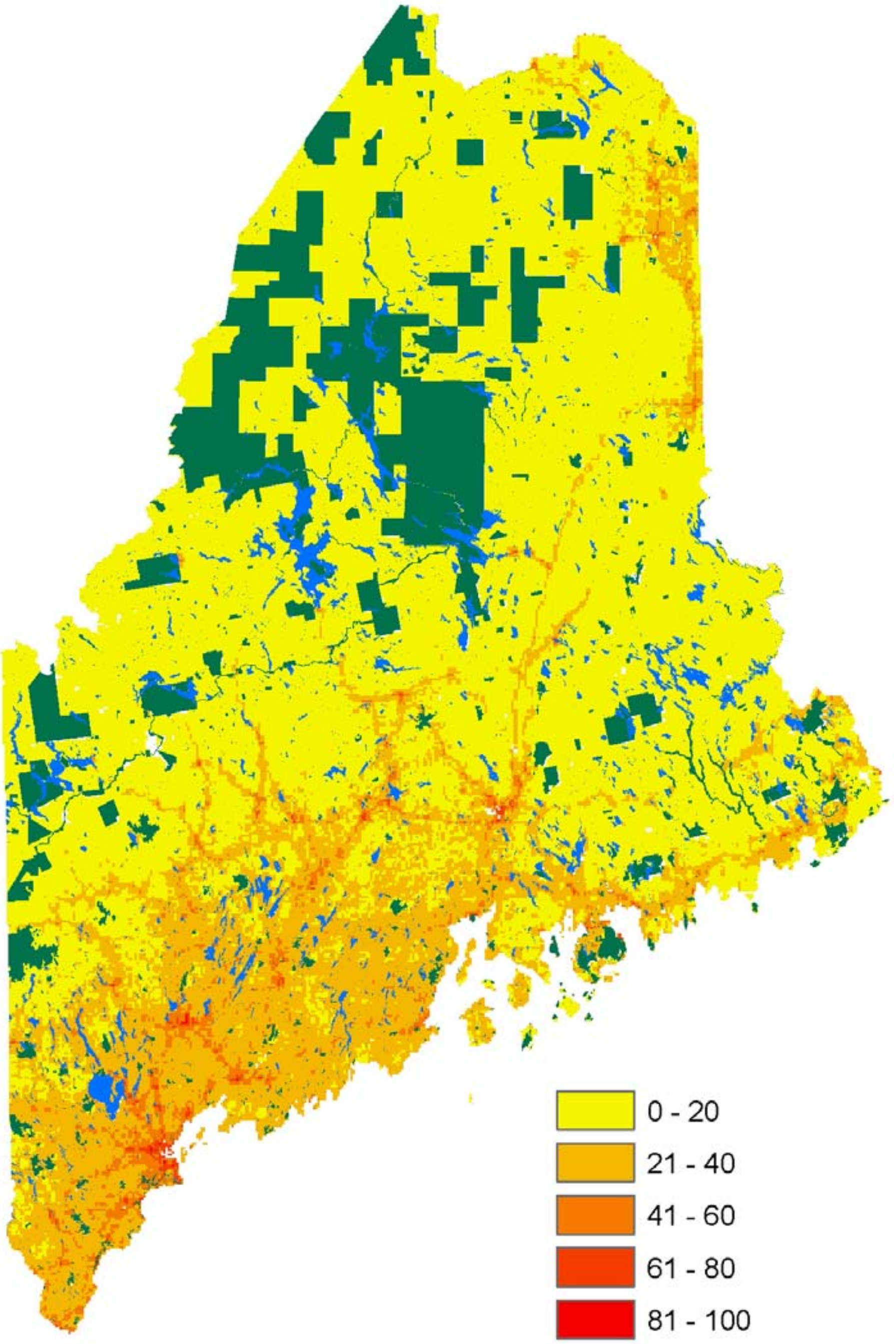

Figure 8
Actual, Predicted, and Forecasted TP Class Distribution (n=531 lakes)

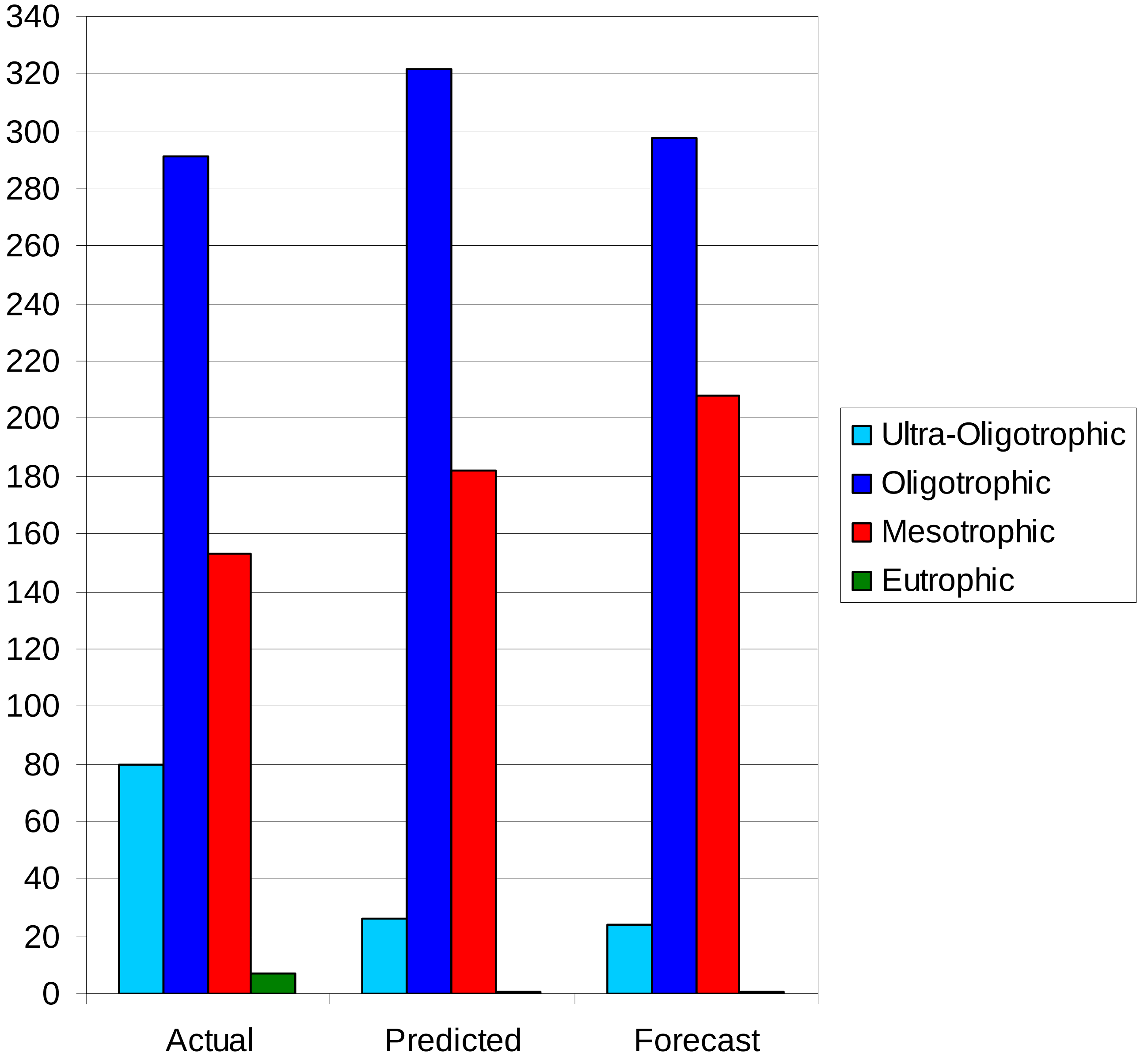

Table 1 Land-cover Change Model - Variable Names and Descriptions

Variable Name	Description
CONV	1 if cell was in an undeveloped land cover class in 1992 and a developed land cover class in 2001; 0 otherwise
AG1992	1 if cell was in agriculture land cover in 1992; 0 Otherwise
NDEV	Percentage of neighboring cells (7 by 7 rectangle) in developed land cover in 1992
LNHELEV	Natural logarithm of distance (measured in meters) to a high elevation area (> 2700 feet)
LNCOAST	Natural logarithm of distance (measured in meters) to the coastline
LNPORTLAND	Natural logarithm of distance (measured in meters) to the City of Portland
LNRIVER	Natural logarithm of distance (measured in meters) to a river
LNLAKE	Natural logarithm of distance (measured in meters) to a lake
LNMAJRD	Natural logarithm of distance (measured in meters) to a major road
SERV10K	1 if cell was located within 10 kilometers of a regional service center; 0 otherwise
MNRD10K	1 if cell was located within 10 kilometers of a minor road; 0 otherwise

Table 2 Land-cover Change Model - Descriptive Statistics*

	Region 1		Region 2	
Variable Name	**Mean**	**Std Dev**	**Mean**	**Std Dev**
CONV	0.3541	0.4782	0.1346	0.3413
AG1992	0.1813	0.3853	0.0730	0.2602
NDEV	5.2193	12.8948	1.0954	5.8883
LNHELEV	11.1470	0.3488	10.4457	1.7917
LNCOAST	9.0180	1.5751	11.1329	1.3753
LNPORTLAND	10.9453	0.7017	12.2932	0.4530
LNRIVER	7.6370	1.1533	7.5816	1.1546
LNLAKE	6.2447	0.9740	6.4763	0.9070
LNMAJRD	7.3519	2.4006	8.8174	2.0928
SERV10K	0.7503	0.4328	0.3946	0.4888
MNRD10K	1.0000	0.0000	0.7998	0.4001

* The Region 1 sample has an overall size of 2,974,810, with 1,053,341 (CONV=1) and 1,921,469 (CONV=0). The Region 2 sample has an overall size of 10,464,162 with 1,408,900 (CONV=1) and 9,055,262 (CONV=0).

Table 3 Model of Total Phosphorus in Maine Lakes: Variable Names, Descriptions, and Descriptive Statistics*

Variables	Units Measured	Mean	Std	Range
TP	ppb	9.5009	6.2154	1 - 61
SECCHI	meters	5.53	2.34	.51 - 14.41
CHLOROPHYLL	μgL^{-1}	5.25	9.78	.5 -158
COLOR	PCU	15.87	14.80	.83 - 115.72
RETENTION TIME	year	1.1412	1.4690	0.0036 - 10.9052
DEPTH	meters	14.8588	11.1410	2.1336 - 96.3168
CATCHMENT AREA	ha	9653.39	30322.27	9.00-367,778.00
LAKE SURFACE AREA	ha	434.0143	1615.22	2.2546-30,542.02
CATCHMENT AREA TO LAKE SURFACE AREA (CTOL)	ratio	30.9086	91.2776	1.4680-1519.17
W_DEV	% DEV - Watershed	4.9802	3.4238	0.06 - 13.44
W_FOREST	% FOR - Watershed	74.5394	6.1353	61.78 - 89.60
W_WETLAND	% WET - Watershed	9.2790	2.8372	4.77 - 15.93
W_AG	% AG - Watershed	4.5744	2.9528	0 - 18.52
B_DEV	% DEV - 500m buffer	4.8882	5.3640	0-41.8707
B_FOREST	% FOR - 500m buffer	60.6279	15.1574	20.4759-95.1613
B_WETLAND	% WET - 500m buffer	7.6218	6.6362	0-47.1351
B_AG	%FOR -500m buffer	2.4280	4.5378	0-30.7380

*n=531

Table 4 Land-Cover Change Model: Binary Logit Model Results*

	Region 1		Region 2	
Variable Name	**Parameter Estimate**	**Standard Error**	**Parameter Estimate**	**Standard Error**
INTERCEPT	2.7915	0.0600	7.1462	0.0292
AG1992	1.0571	0.0033	1.3342	0.0029
NDEV	0.0438	0.0001	0.0705	0.0002
LNHELEV	0.0720	0.0055	0.1081	0.0013
LNCOAST	-0.0754	0.0012	-0.1309	0.0008
LNPORTLAND	-0.1503	0.0023	-0.4412	0.0026
LNRIVER	0.0080	0.0012	-0.1408	0.0008
LNLAKE	-0.1849	0.0014	-0.2400	0.0011
LNMAJRD	-0.1517	0.0007	-0.2426	0.0005
SERV10K	-0.1538	0.0032	0.1927	0.0023
MNRD10K			1.0081	0.0058
-2 LnL (intercept)	3,866,895.4		8,269,072.7	
-2 LnL(covariates)	3,405,011.7		6,390,571.0	
Global Null (β=0); LR test and Pr > Chisquare	461,833.715; <0.0001		1,878,499.69; <0.0001	

*All estimated parameters were significant at the p<0.0001 level.

Table 5 Model of Total Phosphorus in Maine Lakes: Results*

Variable	Parameter Estimate	Standard Error	Pr>|t|	Parameter Estimate	Standard Error	Pr>|t|
Intercept	2.8799	0.13102	<0.0001	2.85175	0.1032	<0.0001
LNDEPTH	-0.4276	0.0317	<0.0001	-0.4266	0.0316	<0.0001
LNCTOL	0.04606	2.40	0.0166	0.04786	0.01873	0.0109
W_WET	-0.0014	0.0071	0.8455			
W_DEV	-0.0029	0.0068	0.6734			
B_WET	0.01632	0.0034	<0.0001	0.01607	0.0033	<0.0001
B_DEV	0.0088	0.0043	0.0414	0.0080	0.0038	0.0351
F, Pr>F	53.95, <0.0001			81.14, <0.0001		
Adjusted R-square	0.3748			0.3769		

* Results are based on OLS estimation (N=531). Dependent variable is the LNTP, the natural logarithm of TP.