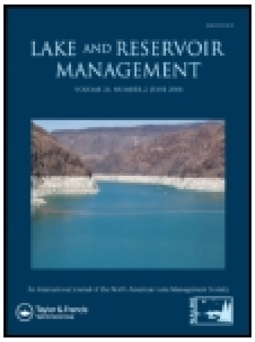

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Assessing local and landscape patterns of residential shoreline development in Michigan lakes

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Abstract

Wehrly KE, Breck JE, Wang L, Szabo-Kraft. L 2012. Assessing local and landscape patterns of residential shoreline development in Michigan lakes. Lake Reserv Manage. 28:158–169.

We evaluated relationships between residential development intensity and littoral zone habitat and disturbance characteristics in 332 Michigan lakes 4 ha and larger. We also developed a landscape-based model to estimate lakeshore status in more than 6500 unsampled lakes. Residential development had strong negative effects on large woody debris and strong positive effects on shoreline armoring and docks at both local and whole-lake scales. Lakes having greater cumulative residential development showed greater littoral zone impacts at local scales. Littoral habitats were more heavily impacted in larger lakes and in lakes in southern Michigan. Results of our predictive modeling identified the following as important predictors of residential shoreline development: the amount of urban land use, public ownership, and wetlands in a 100 m buffer around a lake as well as distance to major population centers. Statewide estimates of shoreline development showed that in southern Michigan only 8% of lakes were undeveloped and that 23% had low and 69% had high development intensity. In contrast, 30% of northern Michigan lakes were undeveloped and 48% had low and only 22% had high development intensity. Land planning policy and lake management should consider cumulative effects of lakeshore development as well as the effects of region and lake type. Our study provides the basis for developing regional strategies to protect, restore, and manage lake ecosystems.

Key words: habitat, lakes, land use, landscape, residential development, shoreline armoring, woody debris

Shorelines are an ecologically and economically important element of lake ecosystems. Natural shorelines provide habitat for aquatic and terrestrial organisms, influence the flow of nutrients and organic materials between land and water, and reduce soil erosion (Schmieder 2004). The recreational and aesthetic opportunities of lakeshores also make them attractive areas for human settlement, and residential development on the landscape is often concentrated around lakes (Schnaiberg et al. 2002, Walsh et al. 2003). Human activities associated with residential shoreline development, however, can alter lake ecosystems, and the ecological integrity of many lakes is currently reduced by degraded shoreline habitat (USEPA 2010). In addition, human population growth and urbanization of rural areas have increased development pressure on lakes, and there is growing concern over the impacts of future lakeshore development (WDNR 1996, Schmieder 2004).

Understanding the consequences of residential development is therefore critical for understanding the ecology of lake ecosystems. A growing number of studies have found negative relationships between lakeshore development and water quality (Moore et al. 2003); habitat structure (Christensen et al. 1996, Jennings et al. 2003, Francis and Schindler 2006, Marburg et al. 2006); and population dynamics and community structure of primary producers (Radomski and Goeman 2001, Jennings et al. 2003, Rosenberger et al. 2008), macroinvertebrates (Banziger 1995, Brauns et al. 2007), and fishes (Bryan and Scarneccia 1992, Jennings et al. 1999, Schindler et al. 2000, Radomski and Goeman 2001, Scheuerell and Schindler 2004, Sass et al. 2006, Wagner et al. 2006). These comparative studies provide much needed information linking shoreline development and key lake characteristics. However, because these studies are based on observations from relatively few lakes (median

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N = 17, max N = 45), it is unclear to what extent the reported relationships can be generalized across a wide range of lake types. Such information is necessary to better identify causal mechanisms and to formulate policies and strategies to protect, enhance, or restore large numbers of lakes across broad regions (Ostendorp 2004, Carpenter et al. 2007).

Assessing the ecological status of shorelines across the landscape is also critical for developing regional management strategies (Ostendorp 2004, Carpenter et al. 2007). Information on the numbers, types, and location of lakes having different levels of residential development is needed to identify resources at risk and to prioritize management actions. Resource agencies typically rely on field observations to assess shoreline status. However, sampling a large number of lakes is cost prohibitive, especially in regions such as Michigan where lakes number in the thousands. Landscape-based models have been used to estimate ecological condition in aquatic systems (Wang et al. 2008, 2010) and may offer a cost-effective alternative for assessing the status of lakeshores at the regional scale. Walsh et al. (2003) found strong relationships between urban land use and the position of lakes in southeast Michigan, and Schnaiberg et al. (2002) used landscape data to predict human settlement patterns around lakes in northern Wisconsin. Results from these studies suggest that predicting residential development from readily-available mapped data is feasible.

In this paper we examined (1) the relationships between residential shoreline development and littoral zone habitat and human disturbance across a broad range of lake types, (2) developed a model to predict development intensity from landscape variables, and (3) characterized broad-scale patterns of shoreline residential development across Michigan.

Methods

Study lakes

Study lakes (Fig. 1) were selected to represent the range of lake types and environmental conditions found in Michigan. All lakes in the state having a surface area of 4 ha and larger and a public access were considered for sampling. From this pool, 332 lakes were randomly selected based on surface area class (small: 4–40 ha; medium: 40–400 ha; large: >400 ha) and Michigan Department of Natural Resources fisheries management unit (Wehrly et al. 2012a). Because of the large gradients in climate, geology, and land use and land cover (land use/cover) in the state that influence human activities and riparian forest types and size structure (Francis and Schindler 2006), study lakes were split into strata based on level III Ecoregions (Omernik 1987); 95% of study lakes occurred in the Northern Lakes and Forest and the Southern Michigan/Northern Indiana Drift Plains Ecoregions. Because of low sample sizes in the remaining Ecoregions, lakes in the Northern Lakes and Forest Ecoregion and Central Hardwood Ecoregion were grouped together as northern lakes, and lakes in the Huron Erie Lake Plain, Southern Michigan/Northern Indiana Drift Plains and Eastern Corn Belt Plains Ecoregions were grouped together as southern lakes.

Littoral zone characteristics and residential shoreline development

Littoral zone characteristics and residential development were estimated in each lake by visual observation from a boat travelling approximately 30 m offshore (Wehrly et al. 2012b). Survey crews travelled parallel to shore and assessed habitat and residential development in 0.3 km segments (hereafter transects). A GPS was used to measure transect distance. Crews assessed conditions in every 0.3 km transect until the entire lake was traversed. Data from individual 0.3 km transects were used to evaluate local-scale relationships between littoral habitat and the intensity of residential development on the adjacent shoreline. Data from all 0.3 km transects within a lake were used to evaluate lake-wide patterns.

We focused on large woody debris (LWD), shoreline armoring, and boat docks as measures of habitat and human disturbance in the littoral zone. We chose these characteristics because they are known to influence aquatic organisms, are often manipulated by property owners, and are easily measured. LWD serves as an important refuge, food source, and spawning habitat for fish (Schindler et al. 2000, Hunt and Annett 2002, Roth et al. 2007). Shoreline armoring may destroy shoreline plants that provide food and cover for invertebrates, which are in turn consumed by fish (Engel and Pederson 1998). Shoreline armoring may also reduce habitat heterogeneity, altering fish assemblage structure (Jennings et al. 1999, Trial et al. 2001). The footprint of boat docks may alter the abundance and species composition of aquatic vegetation and affect fish species composition and nesting behavior (Garrison et al. 2005, Reed and Pereira 2009, Radomski et al. 2010). Finally, boat traffic associated with docks may stir up sediments sufficient to hamper photosynthesis (Yousef et al. 1980, Murphy and Eaton 1983, Asplund 2000).

Study lakes were surveyed from 2002 to 2009. Counts of the number of houses, number of boat docks, and number of pieces of LWD $\geq$ 7.6 cm diameter were made. Houses located within 100 m of shoreline were counted; apartment buildings and condominiums were counted as single dwellings. Pieces of LWD were counted if they were visible

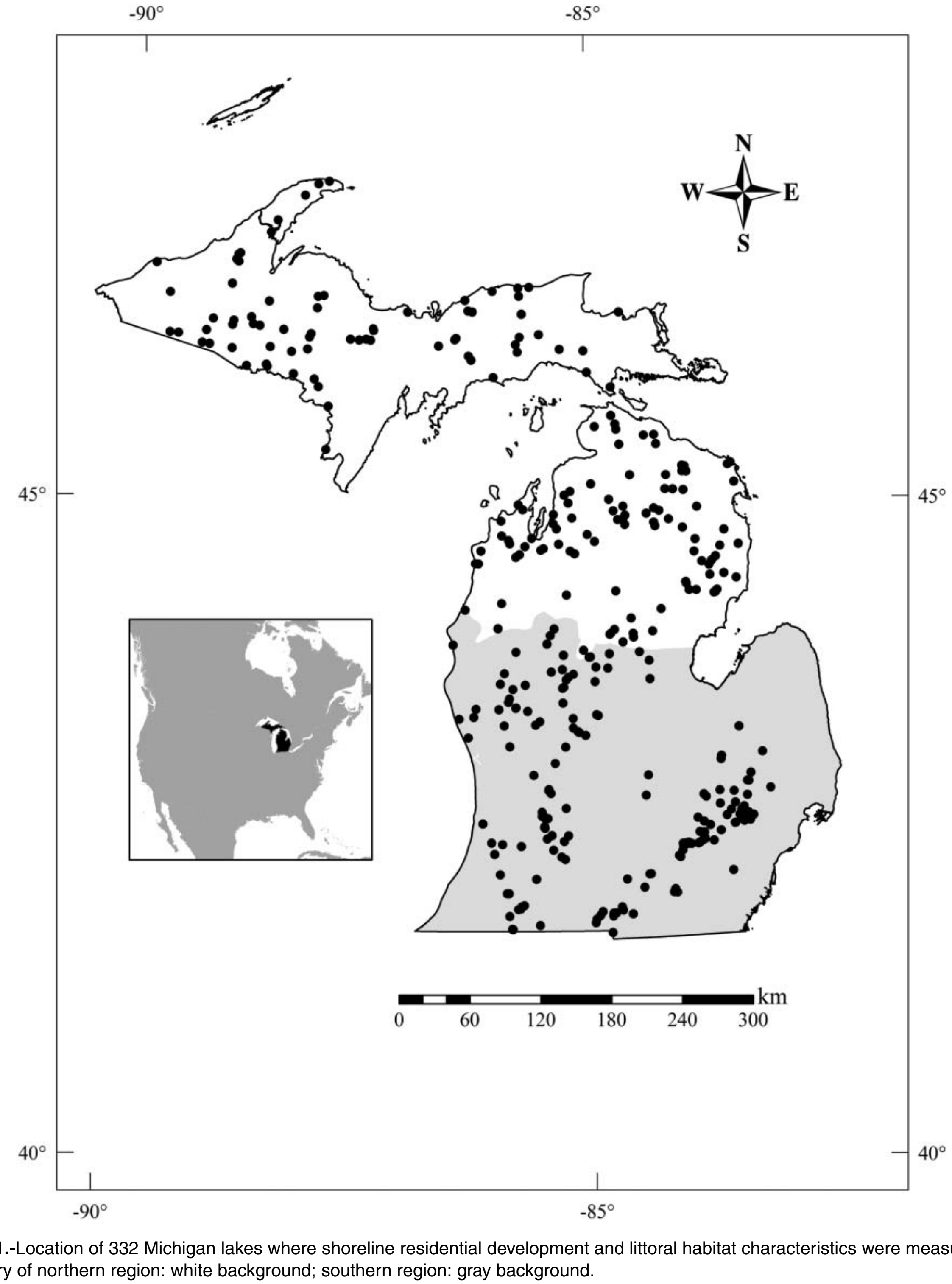

Figure 1.-Location of 332 Michigan lakes where shoreline residential development and littoral habitat characteristics were measured. Boundary of northern region: white background; southern region: gray background.

between the boat and shore. Length of each armored transect was estimated to the nearest 10%. Percent shoreline armoring represents a qualitative estimate of the linear amount of each transect composed of materials intentionally placed to prevent erosion. Presence of sheet piling, concrete, rip-rap, gabions, boulders, and wood was considered shoreline armoring, but survey crews did not estimate proportions of each type.

For each lake, density (number per kilometer of shoreline) of houses, boat docks, and LWD were calculated by dividing the lake-wide count of each variable by lake perimeter. Because the distance travelled by survey crews did not represent the true perimeter of the shoreline, we used lake perimeter measured from maps. Extent of shoreline armoring in each lake was calculated as the average shoreline armoring for all transects in the lake. Intensity of residential development was classified into undeveloped (0 houses/km), low (1–10 houses/km), and high (>10 houses/km) categories following Christensen et al. (1996) and Francis and Schindler (2006).

Landscape data

Readily available mapped data were used to develop predictive models of residential shoreline development intensity and to estimate development intensity in all lakes 4 ha and larger. All natural and manmade lake polygons 4 ha or larger in the state of Michigan were selected from the 1:24,000 National Hydrography Dataset using a geographic information system (GIS; ESRI 2002). Catchment boundaries were delineated for all lakes using GIS algorithms to identify runoff directions based on 30 m resolution Digital Elevation Model and to restrict the outmost catchment boundaries using 12-digit Hydrological Unit (HU) or aggregated HUs that were developed by the Michigan Department of Environmental Quality. Catchments were defined as the land area where surface water drains directly into lakes. In the case of lakes with tributary inputs, catchments included land area where surface water drains into rivers and then into lakes. A 100 m buffer was also created around the shoreline of each lake. Landscape data were summarized for the catchment and buffer of each lake.

Measures of morphology, land use/cover, and distance to major roads and cities were summarized for each lake. Measures of lake morphology included lake area, catchment area, shoreline development index [$D = L/(2^*(\pi^*A)^{1/2})$, where L is lake perimeter and A is lake area (Orth 1989)] and lake fetch (measured as the longest unobstructed distance across a lake). Land use/cover was measured from 2001 Michigan Land Use/Cover Data (http://www.mcgi.state.mi.us/mgdl). The amount of land in public ownership was estimated from the conservation and recreation lands dataset (http://www.ducks.org/conservation/glaro/carl-gis-layer).

Statistical analyses

Relationships between shoreline residential development and littoral zone characteristics were evaluated at local (transect) and lake-wide spatial scales. At the local scale the effect of residential development was evaluated using analysis of covariance with region (north and south) and transect development (undeveloped, developed) as main factors. In this analysis, lake-wide development intensity (homes/km) was included as a covariate to evaluate whether cumulative residential development influenced littoral zone habitat and disturbance at the local scale. Lake surface area was also included as a covariate to evaluate how lake size might influence local scale conditions in the littoral zone. At the whole-lake scale the effect of residential development on littoral zone characteristics was evaluated using analysis of covariance with region (north and south) and development intensity (undeveloped, low, high) as main factors. In this analysis, lake area was included as a covariate to determine if the influence of development varied as a function of lake size. All variables were transformed when necessary to meet assumptions of normality.

Classification tree models that predict shoreline residential development intensity as a function of landscape data were developed using R version 2.9.1 and the rpart library (R Development Core Team 2010). Classification trees models repeatedly split a dataset into groups that are as homogeneous as possible. These repeated splits form a branching diagram or tree. Conditions for defining a split are based on all possible values of all independent variables considered. The model algorithm selects the independent variable that minimizes the impurity within each group, and all independent variables are considered in subsequent splits (Olden et al. 2008). Classification tree size was determined by cross validation ($N = 10$), and trees were grown using a complexity factor of 0.001 and a minimum bucket size of 5 (Breiman et al. 1984). Model training and validation sets were created by randomly splitting the lake dataset in half. Classification models were constructed using the training set, and predictive ability of the final model was determined by calculating classification error rates using the validation set. To determine shoreline residential development for all lakes 4 ha and larger in the state, we predicted development intensity for 6544 unsampled lakes based on the environmental variable values defined in the classification tree model. Landscape pattern of shoreline residential development was characterized by summarizing the percentage of lakes predicted to have no development, low development, and high development and mapping lake locations.

Results

Study lakes

Study lakes represented a broad range in morphology, catchment characteristics, and shoreline residential development, and they varied between regions (Table 1). There were more large (>400 ha) lakes in the north, which resulted in lakes having higher values of fetch and catchment area for the northern lakes. Northern lakes had more forest in the

Table 1.-Morphological, catchment, and residential development characteristics of study lakes in northern (N = 168) and southern (N = 164) Michigan.

	Region					
	North			South		
Lake Characteristic	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**	**Maximum**
Surface Area (ha)	4.1	80.4	8,124.1	5.9	63.0	1,712.5
Fetch (km)	0.4	1.6	18.9	0.4	1.4	7.9
SDI	1.1	1.8	8.8	1.1	1.9	7.6
Catchment Area (ha)	4	1,045	364,465	10	787	592,226
Percent Wetland	0	13.0	63.0	0	13.0	31.0
Percent Agriculture	0	0	56.0	0	20.0	78.0
Percent Urban	0	2.0	20.0	0	5.0	52.0
Percent Forest	12.0	66.0	96.0	5.0	35.0	95.0
Residence Density (no./km)	0	9.1	50.7	0	16.6	66.4

catchment whereas southern lakes had more agriculture and urban in the catchment. Shoreline residential development also differed between regions, with northern lakes having lower median and maximum values of residence density than southern lakes (Table 1).

Local patterns

LWD density at the local level was related to region and to residential development at local and lake-wide scales. LWD density was significantly lower in developed transects in both northern and southern lakes (Table 2; Fig. 2). The interaction between region and local development was also significant (Table 2), with less LWD occurring in both developed and undeveloped transects in southern lakes than developed and undeveloped transects in northern lakes (Fig. 2). LWD density within transects covaried significantly with lake-wide development intensity (Table 2), suggesting a cumulative negative effect of residential development on the amount of LWD found at individual transects. LWD density within transects also covaried significantly with lake surface area (Table 2), suggesting that the amount of LWD found at individual transects was lower in larger lakes.

Table 2.-Summary of analysis of covariance results showing influence of local residential development (undeveloped, developed) and region (north, south) on local scale density of large woody debris (LWD), percent shoreline armoring, and dock density. Lake-wide residential development intensity (number/km) and lake surface area (ha) were included as a covariate in each model.

Model	**Main factor**	**Covariate**	**df**	**F**	**P**
LWD density	Region		1	312.7	<0.001
	Local development		1	185.8	<0.001
	Region × development		1	47.2	<0.001
	Error		4374		
		Lake-wide development	1	45.2	<0.001
		Lake surface area	1	6.7	0.010
Armoring	Region		1	70.5	<0.001
	Local development		1	894.6	<0.001
	Region × development		1	12.0	0.001
	Error		4374		
		Lake-wide development	1	182.7	<0.001
		Lake surface area	1	170.4	<0.001
Dock density	Region		1	2.6	0.108
	Local development		1	3448.3	<0.001
	Region × development		1	50.2	<0.001
	Error		4374		
		Lake-wide development	1	302.4	<0.001
		Lake surface area	1	24.5	<0.001

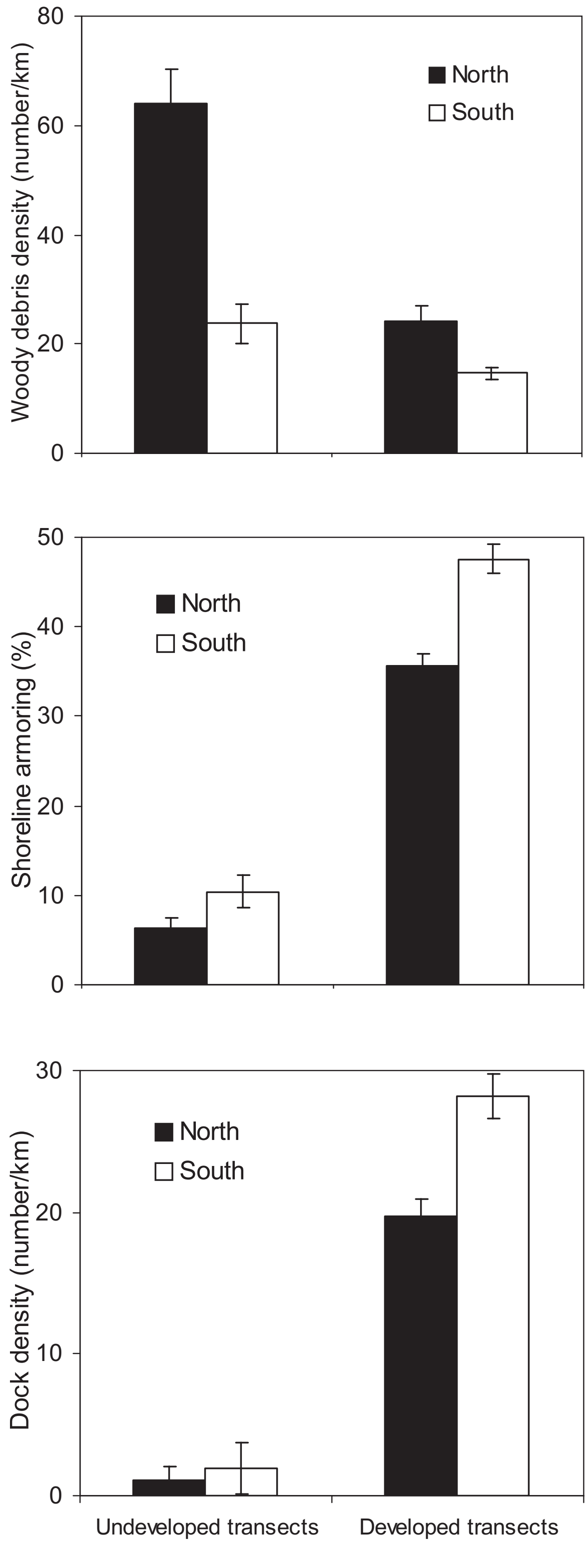

Figure 2.-Mean large woody debris density, percent shoreline armoring, and boat dock density for undeveloped and developed transects in northern and southern Michigan lakes. Error bars represent 2 standard errors.

Shoreline armoring at the local level was also related to region and to residential development at local and lake-wide scales. Percent of shoreline armored was significantly higher in developed transects in both northern and southern lakes (Table 2; Fig. 2). The interaction between region and local development was also significant (Table 2), with more shoreline armoring occurring in developed transects for southern lakes than for northern lakes (Fig. 2). The extent of shoreline armoring within transects covaried significantly with lake-wide development intensity (Table 2), suggesting a cumulative positive effect of residential development on the extent of shoreline modification at the local level. The extent of shoreline armoring within transects also covaried significantly with lake surface area (Table 2), indicating that larger lakes tended to have more shoreline modification at the local level.

Boat dock density at the local level was significantly higher in developed transects in both northern and southern lakes (Table 2; Fig. 2). The interaction between region and local development was also significant (Table 2), with more docks occurring in developed transects for southern lakes than for northern lakes (Fig. 2). Dock density within transects covaried significantly with lake-wide development intensity (Table 2), suggesting a cumulative positive effect of residential development on the number of docks at the local level. Dock density within transects also covaried significantly with lake surface area (Table 2), indicating that larger lakes tended to have a higher density of docks at the local level.

Lake-wide patterns

LWD density at the whole-lake scale was related to region, lake-wide development intensity, and lake surface area. LWD density declined significantly with increasing development, and the northern lakes had significantly higher densities of LWD than southern lakes (Table 3; Fig. 3). The interaction between region and development intensity was significant (Table 3). The northern lakes exhibited a progressive decline from 140 LWD/km for undeveloped lakes, to 40 LWD/km for low development density lakes, and to 15 LWD/km for high development density lakes. In contrast, the southern lakes exhibited reductions from 50 LWD/km for undeveloped lakes to <5 LWD/km for both low and high development density lakes (Fig. 3). Lake-wide density of LWD covaried significantly with lake surface area (Table 3), with larger lakes having less woody debris.

Extent of shoreline armoring at the whole-lake scale was also related to region, lake-wide development intensity, and lake surface area. Percent of shoreline armored increased significantly with increasing development, and southern lakes had significantly more armoring than northern lakes (Table 3;

Table 3.-Summary of analysis of covariance results showing influence of lake-wide residential development intensity (undeveloped, low, high) and region (north, south) on lake-wide density of large woody debris (LWD), percent shoreline armoring, and dock density. Lake surface area was included as a covariate in each model.

Model	Main factor	Covariate	df	F	P
LWD density	Region		1	39.9	<0.001
	Development		2	17.3	<0.001
	Region × development		2	4.2	0.015
	Error		320		
		Lake surface area	1	8.8	0.003
Armoring	Region		1	13.2	<0.001
	Development		2	93.2	<0.001
	Region × development		2	3.9	0.020
	Error		320		
		Lake surface area	1	126.4	<0.001
Dock density	Region		1	1.9	0.164
	Development		2	471.6	<0.001
	Region × development		2	2.8	0.060
	Error		320		
		Lake surface area	1	<0.1	0.838

Fig. 3). The interaction between region and development intensity was significant (Table 3), with southern lakes with high residential development exhibiting the greatest amount of shoreline armoring (Fig. 3). Lake-wide shoreline armoring covaried significantly with lake surface area (Table 3); larger lakes had a higher proportion of armored shoreline.

Unlike LWD and shoreline armoring, lake-wide boat dock density was only related to lake-wide development intensity (Table 3; Fig. 3). Boat dock density increased significantly with increasing levels of residential development (Table 3). Mean dock density in highly developed lakes seemed to be greater in the south (Fig. 3), but this difference was not significant.

Statewide patterns

The final classification tree was composed of 5 leaves, with land use/cover in the 100 m buffer and distance to Detroit the best predictors of statewide patterns of shoreline residential development intensity (Fig. 4). In the first split, lakes having 10% or more urban land use in the buffer were classified as having high development. The second split in the tree indicated that lakes having a large percentage (≥76%) of land in public ownership tended to be undeveloped. Lakes having less land in public ownership were again split based on proximity to Detroit. Lakes at least 331 km from Detroit had low shoreline residential development. Lakes that were closer to Detroit tended to have high levels of development if the amount of wetlands around a lake was <42%. Lakes that were closer to Detroit and had a higher percentage of wetlands in the buffer tended to have low development.

Overall error rate of the model was 24%. Model performance varied by shoreline residential development category. Based on the validation dataset, classification error rates were 21% for undeveloped lakes, 41% for lakes having low levels of development, and 15% for lakes having high levels of development.

Predicted shoreline residential development for all lakes 4 ha and larger revealed spatial variation in development intensity across Michigan (Fig. 5). Lakes that were undeveloped or that had low development were distributed throughout the state with the highest concentrations occurring in the Upper Peninsula. Lakes having high levels of shoreline residential development were found primarily in the Lower Peninsula and often in close proximity to lakes that were predicted to be undeveloped or to have low levels of development. Nearly a third of the northern lakes were predicted to be undeveloped while <10% of southern lakes were undeveloped (Fig. 6). Northern Michigan (48%) was predicted to have a larger proportion of lakes having low levels of development whereas the majority (69%) of southern Michigan lakes was expected to have high levels of shoreline residential development (Fig. 6).

Discussion

Residential shoreline development was strongly correlated with habitat and human disturbances in littoral zones across

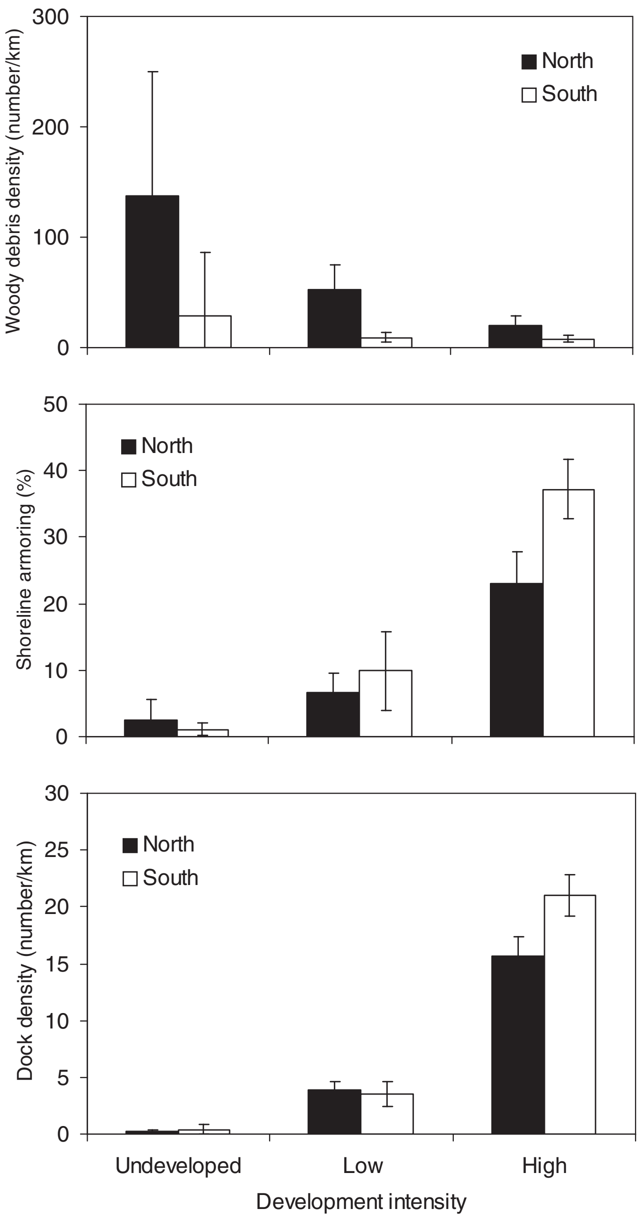

Figure 3.-Lake-wide mean large woody debris density, percent shoreline armoring, and boat dock density as a function of shoreline residential development intensity in northern and southern Michigan lakes. Error bars represent 2 standard errors.

a broad range of lake types. We found significant declines in LWD and significant increases in shoreline armoring and boat docks with increasing levels of development. Our results support smaller-scale studies that have shown losses in woody debris with development (Christensen et al. 1996, Jennings et al. 2003, Francis and Schindler 2006, Marburg et al. 2006). Our study is the first to quantify relationships between dwelling density and intensity of littoral zone disturbances such as shoreline armoring and boat dock density. Because shoreline armoring and boat docks can influence abundance and composition of aquatic vegetation, macroinvertebrates, and fishes (Jennings et al. 1999, Asplund 2000, Trial et al. 2001, Garrison et al. 2005, Radomski et al. 2010), understanding the prevalence of these disturbances and their relationship to dwelling density is critical for developing shoreline development policies to protect lake ecosystems.

We also found that alteration of the littoral zone at the local scale was influenced by the presence of dwellings on the adjacent shore and by the intensity of shoreline development on the entire lake. The cumulative effects of shoreline development on human disturbance of littoral areas have received relatively little attention in the literature. In a study of 44 Minnesota lakes, Radomski and Goeman (2001) found that site-level losses of emergent and floating-leaf vegetation were related to residential development on the entire lake shoreline. Similarly, Jennings et al. (2003) found that substrate embeddedness, woody debris, and emergent and floating vegetation were negatively related to lake-wide residential development in 16 Wisconsin lakes. Our results, together with the findings from Minnesota and Wisconsin lakes, suggest that shoreline residential development has cumulative effects on littoral habitats that are pervasive and widespread.

We also found strong regional effects. Lakes in southern Michigan have less LWD, more shoreline armoring and higher boat dock density than northern lakes. This trend may have resulted from higher levels of residential shoreline development in the south (mean residence density was 16.6 for southern lakes, 9.1 for northern lakes). However, when we restricted the upper bounds of residential development to $\leq$30 homes/km, developed transects in southern lakes still had significantly less woody debris and more armoring and boat docks than northern lakes. Regional variation in littoral habitat and disturbance likely results from a combination of natural and anthropogenic factors (Marburg et al. 2006, Carpenter et al. 2007). Differences in forest composition may, in part, explain differences in LWD between regions. Francis and Schindler (2006) attributed differences in LWD between Pacific Northwest and northern Wisconsin lakes to differences in riparian forest types between regions. In Michigan, northern forests are dominated by evergreens and southern forests are dominated by hardwoods. It is not known, however, if these forest community differences result in differences in abundance and size distribution of riparian trees between northern and southern Michigan lakes. Differences in LWD among regions may also result from historic land-use practices. By the early 20th century, most of Michigan's forests were clearcut. After the logging boom, land in the southern portion of the state was converted to agriculture, but in the north forests were allowed to regenerate because

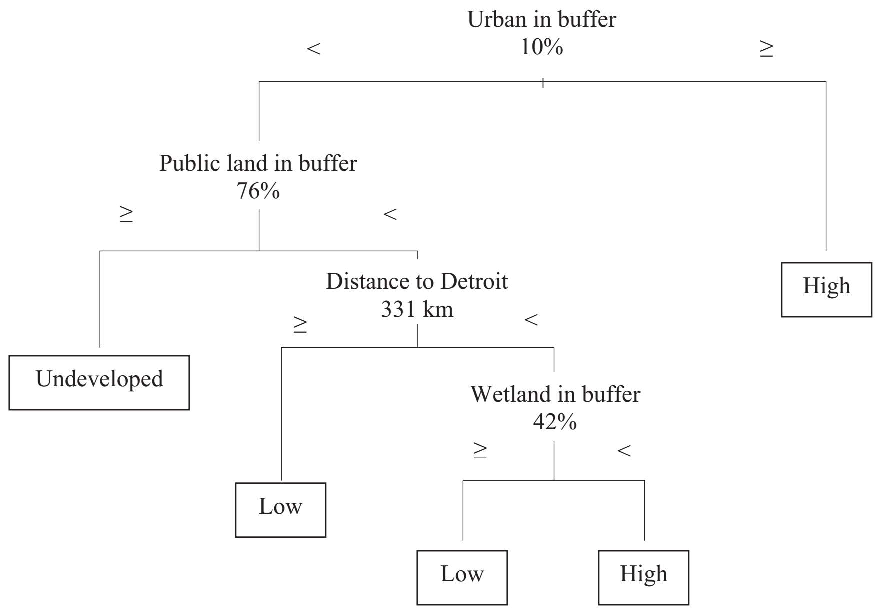

Figure 4.-Landscape-based classification tree model predicting shoreline residential development intensity.

poor soils and short growing seasons limited agricultural development. In our study, northern lakes had almost twice as much forest in their catchment as southern lakes, suggesting that the higher amount of woody debris in northern lakes results, in part, from the greater amount of forest available for recruitment to littoral habitats in this region.

Variation in littoral zone conditions across Michigan may also result from regional differences in socioeconomics. Southern Michigan is characterized by higher population density and a larger economy. As a result, demands for swimming beaches, unobstructed boating lanes, and lake views are likely greater in this portion of the state. Higher boat traffic in the south may also motivate property owners to increase shoreline armoring to prevent shoreline erosion caused by excess power from waves and boat wakes. Regardless of the cause, our results indicate that there are significant regional differences in the intensity with which property owners modify littoral habitats, especially in lakes that are highly developed.

We also found that larger lakes tended to have less woody debris and more shoreline armoring. Larger lakes have greater fetch, and woody debris may be more likely to be moved offshore by wave energy (Marburg et al. 2006). Similarly, higher wave energy on larger lakes may also result in higher amounts of shoreline armoring to prevent erosion.

Our predictive model enabled us to estimate the intensity of residential shoreline development for all lakes 4 ha and greater ($n = 6544$) and to characterize statewide patterns of residential shoreline development for the entire resource. We found that more than 60% of the lakes in Michigan have been developed; in the southern portion of the state, few undeveloped lakes remain, and the majority of the lakes have high levels of development. In contrast, in the northern portion of the state, nearly a third of the lakes are undeveloped, and the majority of the lakes have low levels of development.

Our model of residential development suggested that development intensity was related to landscape characteristics within a 100 m buffer around a lake and to a lake's distance from the population center of southern Michigan. Urban development of the landscape tends to be focused near lakes (Schnaiberg et al. 2002, Walsh et al. 2003), and not surprisingly, we found that a threshold of 10% urban land use in the lake buffer resulted in high levels of residential shoreline development. We found that development intensity was inversely related to the amount of publicly owned land and wetlands. In a study of building intensity around lakes in Vilas County, Wisconsin, Schnaiberg et al. (2002) reported a similar effect of wetlands but that publically owned land was associated with higher levels of development. Schnaiberg et al. (2002) suggested that the positive relationship between the amount of publicly owned land and development intensity may have resulted from landowners being attracted to lakes having some level of natural shoreline. The contrasting influence of public lands between the 2 studies likely results from the broader range of lake types and shoreline development included in our analysis. We also

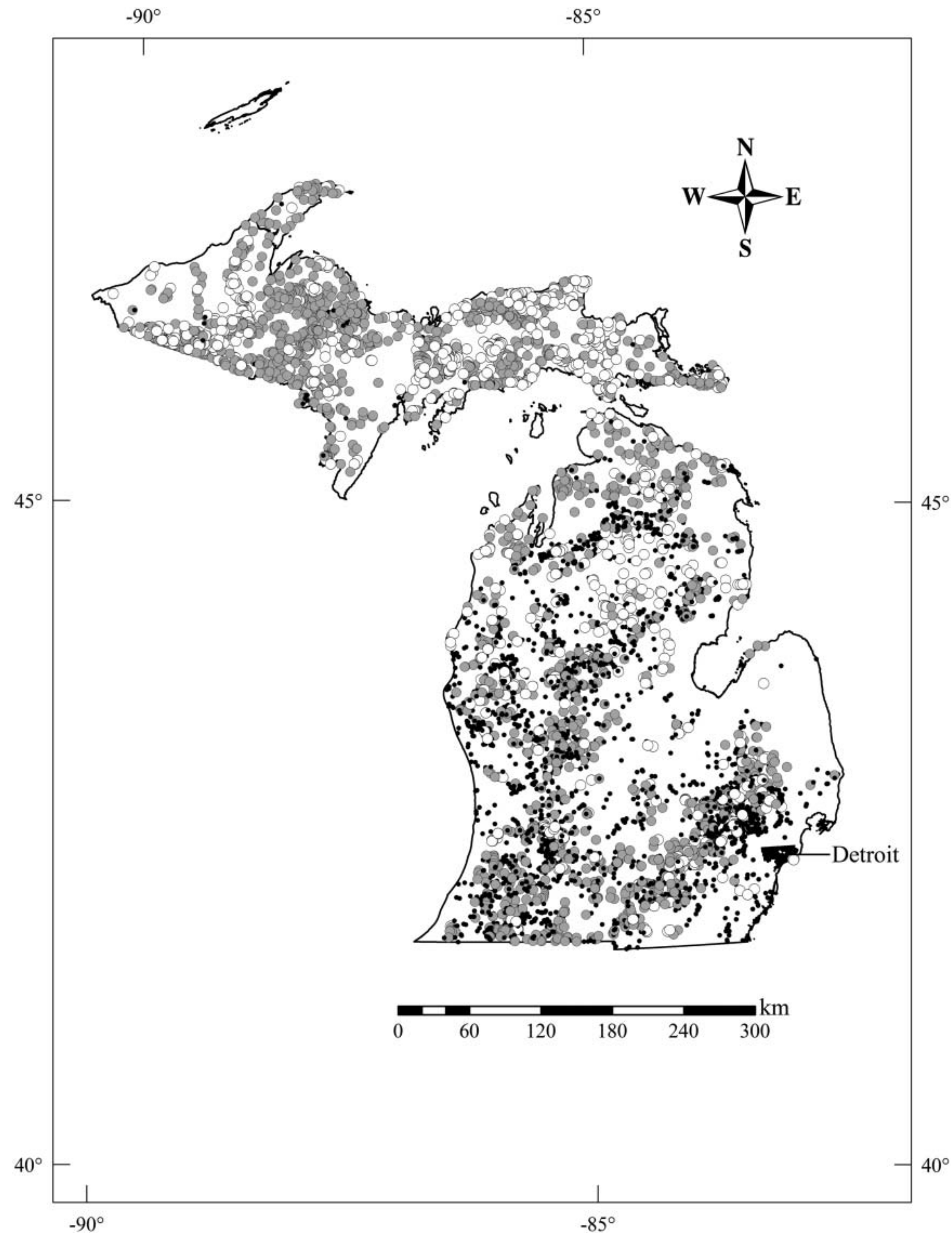

Figure 5.-Predicted shoreline residential development intensity for 6544 Michigan lakes 4 ha and larger. Open circles: undeveloped lakes; gray circles: low development lakes; black circles: high development lakes.

found that lakes farther from Detroit had lower residential development intensity. This trend may reflect regional differences in population density and travel costs (Schnaiberg et al. 2002).

Management implications

We found that lakes having greater cumulative residential development showed greater littoral zone impacts at local

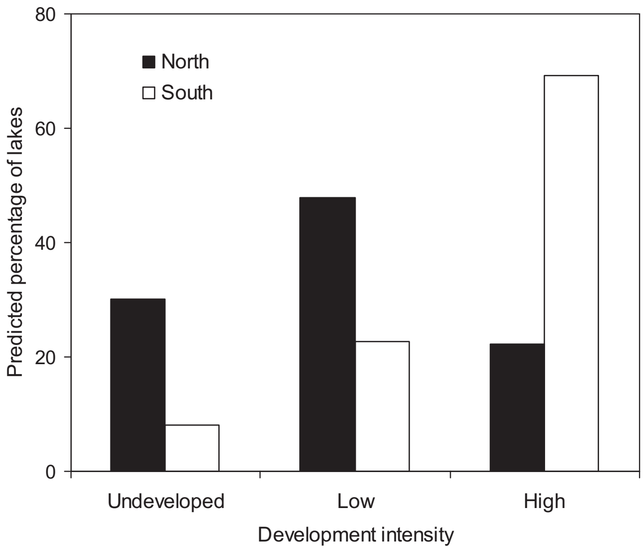

Figure 6.-Frequency of shoreline residential development in northern and southern Michigan lakes predicted from classification tree models.

scales. Current regulation of shoreline development and alteration of the littoral zone currently focuses on individual parcels. This piecemeal approach limits the impact at individual sites but does not protect lakes against the cumulative impacts that gradually accrue over time. Additional work is needed to develop policies that take into account the cumulative impacts of incremental shoreline development.

Model predictions of shoreline development provide valuable information on the extent and intensity of disturbance for the entire population of lakes in Michigan. Such information can be used by land planners and resource managers to prioritize management efforts. For example, given their relative scarcity in southern Michigan, undeveloped and low development lakes may be high priorities for conservation. Land ownership data can be overlaid with the estimated location of undeveloped and low development lakes to identify gaps in public ownership and opportunities for protection through zoning, land use planning, conservation easements, or land acquisition. Our predictive model highlights the importance of public land and wetlands in influencing development intensity. As development pressures of rural landscapes increase, management strategies that conserve public lands and wetlands may be critical for protecting lakes from the impacts of future shoreline development.

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