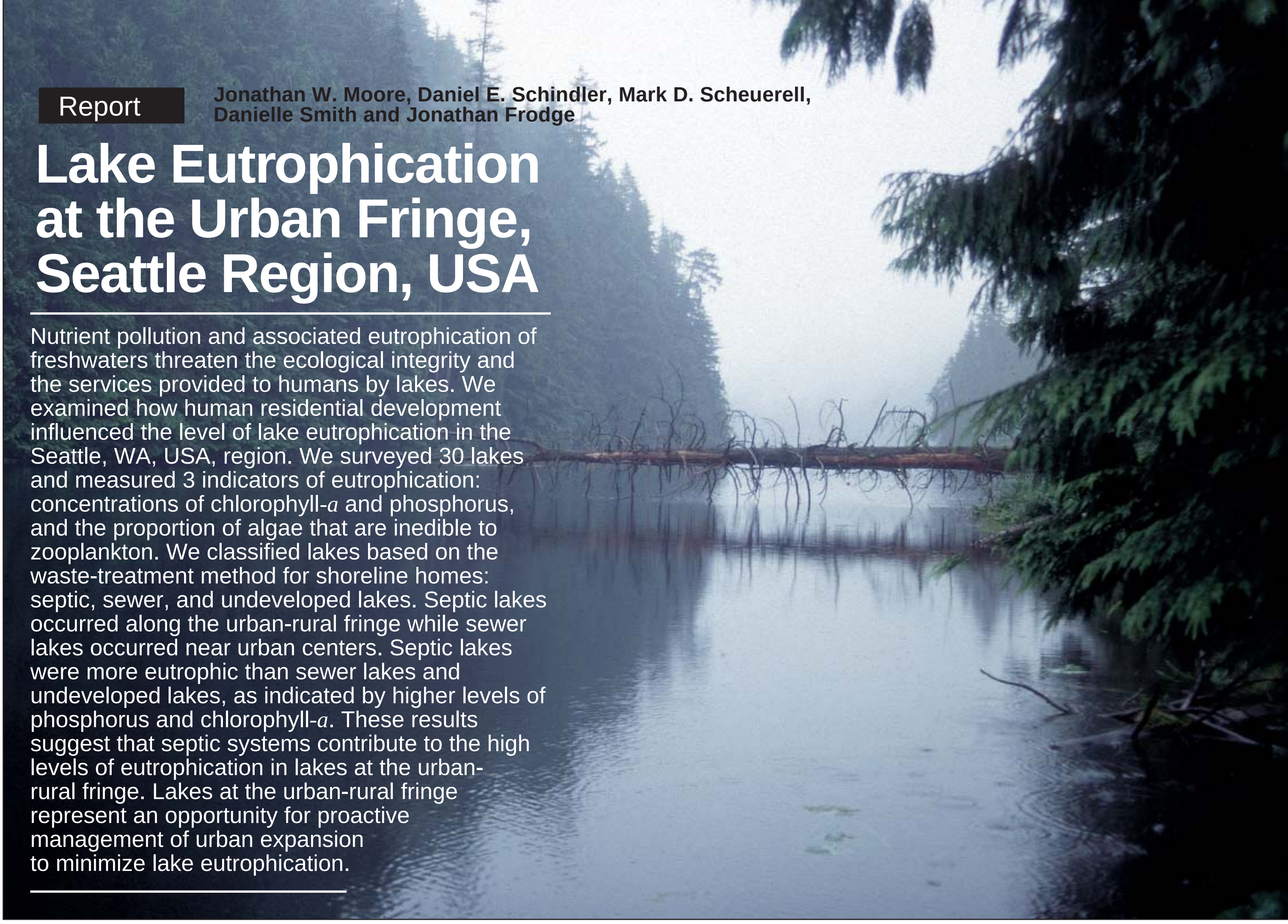
Report

Jonathan W. Moore, Daniel E. Schindler, Mark D. Scheuerell,
Danielle Smith and Jonathan Frodge

Lake Eutrophication at the Urban Fringe, Seattle Region, USA

Nutrient pollution and associated eutrophication of freshwaters threaten the ecological integrity and the services provided to humans by lakes. We examined how human residential development influenced the level of lake eutrophication in the Seattle, WA, USA, region. We surveyed 30 lakes and measured 3 indicators of eutrophication: concentrations of chlorophyll-*a* and phosphorus, and the proportion of algae that are inedible to zooplankton. We classified lakes based on the waste-treatment method for shoreline homes: septic, sewer, and undeveloped lakes. Septic lakes occurred along the urban-rural fringe while sewer lakes occurred near urban centers. Septic lakes were more eutrophic than sewer lakes and undeveloped lakes, as indicated by higher levels of phosphorus and chlorophyll-*a*. These results suggest that septic systems contribute to the high levels of eutrophication in lakes at the urban-rural fringe. Lakes at the urban-rural fringe represent an opportunity for proactive management of urban expansion to minimize lake eutrophication.



A lake without shoreline development. Undeveloped lakes were less eutrophic than lakes with shoreline houses. Photo: D. Schindler.

INTRODUCTION

Residential development in the United States has increased substantially over the last 50 years. Much of that increase has been concentrated in urban areas, where nearly 80% of the United States population currently resides (1). As people move from rural regions and urban centers to the city boundaries and suburbs, cities are growing larger, both in population and in area (1). As cities expand, developers convert land from agricultural areas and forested regions into urban and suburban areas (2, 3). Thus, at the edge of the urban area, the urban-rural fringe, there is often a patchwork of small agricultural and forested areas fragmented by construction sites, newly built residential and commercial development, and older, formerly outlying residences that have been engulfed by the urban sprawl (1, 2).

Population growth, and specifically residential development, is associated with many environmental impacts (3), including nutrient pollution and subsequent eutrophication of lakes (4–6). Eutrophication of lakes refers to a group of symptoms that lakes generally display when they have been overloaded by nutrients, namely nitrogen and phosphorus (7, 8). These symptoms include a disruption of the natural ecological state of lakes (9), including higher primary production, higher algae biomass, and a shift in the algal community to a larger proportion of large, blue-green algae that can be inedible to herbivorous zooplankton (9) and toxic to humans, livestock, and pets (10, 11). Thus, eutrophication often leads to lakes that are less economically beneficial and aesthetically desirable to humans (9, 12, 13).

Phosphorus pollution is an important cause of lake eutrophication (7, 8). While point sources of phosphorus pollution have been increasingly controlled in the United States since the Clean Water Act (1972) (9), diffuse and ill-defined nonpoint sources continue to pollute lakes throughout North America (6). Urban areas tend to have point sources of nutrient pollution such as sewage outputs, while rural areas primarily have nonpoint sources of nutrient pollution (6). Some nonpoint sources are specifically associated with development along the urban fringe, including runoff from small construction sites and septic systems (6).

Lakeshore urbanization generally follows a typical progression: an undeveloped lake is colonized by several outlying homes on septic systems, followed by increasing residential development, land and riparian zone clearing, loss of littoral coarse woody debris, more subdivision, until maximum human population density is reached. However, as lakeshores are further developed, there is often increasing infrastructure such as sewer systems to export human waste to treatment plants.

Whether lakes in urban centers or lakes along the urban fringe suffer more from eutrophication remains unanswered. Lakes in urban centers may be more eutrophic because they have higher densities of humans and associated human impacts (4, 5, 14). If so, then we would predict that lake eutrophication would be correlated with shoreline residential development. Alternatively, lakes along the urban fringe could be more eutrophic due to pollution from nonpoint sources such as septic systems or other sources that are not controlled by infrastructure or regulations (15), which may not be directly proportional to local shoreline population levels.

Patterns of eutrophication along urban-rural gradients have not been described in previous studies. Increased levels of eutrophication have been attributed to urbanization by some studies (4, 14, 16, 17). However, there have been instances of human lakeshore development that did not lead to eutrophication (18). Other cases of eutrophication have been attributed to agricultural pollution (19–22), which would be more likely to be an important factor along the urban-rural fringe (1).

We examined the importance of residential development as a cause of nutrient pollution, and specifically the degree of water quality impairment in a set of lakes along an urban-rural gradient of a large US population center. We asked 2 questions: *i*) Where in the greater urban area are conditions of eutrophication the most intense? *ii*) What factors correlate with lake eutrophication?

MATERIALS AND METHODS

The Seattle, WA, region is the largest and most intensely urbanized region in the Pacific Northwest of the United States. The Greater Seattle area contains over 2 million people in an area that spans over 5400 km^2 and has increased in population by over 25% in the last 20 years. The Seattle region is an ideal study area to investigate the impacts of human residential development because of the high rates of urban expansion and the sharp gradient from the urban center to rural landscapes.

During June to August of 1998, we surveyed 30 lakes for indicators of eutrophication. We sampled each lake one time. While there could have been seasonal variation over the summer of the measured parameters, the lakes were surveyed in a random order, thus any seasonal patterns would simply have minimized the results, rather than biasing them. Of the 30 lakes, we surveyed 25 lakes in the Greater Seattle region (Fig. 1). These 25 lakes were selected to span the maximum gradient of human residential development, ranging from lightly developed lakes at the urban-rural boundary to lakes whose shoreline is 100% covered with residential development. To isolate the impacts of development, we surveyed 5 reference lakes that did not have any residential development along their shoreline or in their watershed, at the University of British Columbia Malcolm Knapp Research Forest (UBC) in southwest British Columbia, Canada. These reference lakes lie roughly 150 km north of Seattle on similar geology and are in the same climatic zone as the lakes in the Greater Seattle region. The studied lakes ($n = 30$) were physically similar, and all lakes were monomictic, with a mean depth of 8 m (± 0.9 SE), an average surface area of 22 ha (± 3.1 SE), and an average watershed area of 297 ha (± 52 SE) (23). In addition, all of these lakes lie 35–1121 m a. s. l. (23), and all have some combination of stocked or native populations of rainbow trout (*Oncorhynchus gairdnerii*), cutthroat trout (*Oncorhynchus clarkii*), and largemouth bass (*Micropterus salmoides*). The suite of study lakes was chosen to minimize physical differences among all lakes, while still spanning a full range of human residential development intensity. In addition, we surveyed Lake Washington, which is larger than the other lakes, but was included because it is a key urban lake in Seattle that has had a history of water quality problems, including eutrophication (17).

At each lake we quantified the level of local residential development by visually assessing the proportion of shoreline that was developed for residential or industrial use. We also classified the lakes into 3 categories of development based on waste treatment: *i*) "undeveloped" lakes are the reference lakes that had 0% residential development; *ii*) "sewer" lakes only have houses serviced by sewage systems; and *iii*) "septic" lakes have one or more houses with active septic systems. Thus, lakes with houses on sewer systems had infrastructure to transport human waste to a waste-processing plant outside of the lake drainage area, while septic lakes had houses that processed their waste in local septic fields. We obtained information about local sewage treatment by contacting local water utility administrators. The administrators would not disclose the number of homes on septic systems, but indicated the presence or absence of septic systems along the lakeshore. We measured the degree of eutrophication with 4 metrics: epilimnetic and hypolimnetic total phosphorus concentration ($\mu g\ L^{-1}$), epilimnetic chlorophyll-*a* concentration ($\mu g\ L^{-1}$), and the proportion of inedible phytoplankton.

We also examined historical descriptive data on the lakes, and their drainage basins as controlling factors for eutrophication (23). These data were used to examine historical factors that could affect the current level of eutrophication. The information about the land use in the drainage basin was first compensated to remove the surface area of the lake from the calculations of land use in the drainage basin surface area, as

$$D_C = (D_I/(100\%-D_L)),$$

where D_C represents the compensated percent land use of interest, D_I represents the uncompensated percent land use of interest, and D_L represents the percent of the drainage basin occupied by the lake. Hereafter, all drainage land-use values refer to values that were compensated.

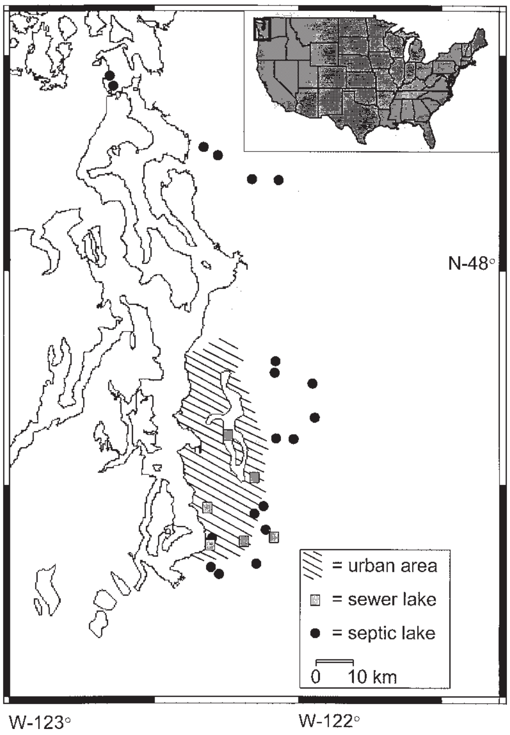


Figure 1. Locations of developed lakes in the Seattle, WA, region that were considered in the study. The inset shows the location of the Seattle, WA, region in relation to the rest of the USA. The undeveloped reference lakes (*n* = 5) are not included in this map, but are located at 49°16' N latitude, 122°30' W longitude. Lakes with houses on sewer systems (*n* = 6) are represented by squares, while lakes with houses on septic systems (*n* = 19) are represented by circles. The hatched area represents the greater Seattle region.

We measured both epilimnetic and hypolimnetic total phosphorus as parameters of eutrophication. Epilimnetic phosphorus represents the amount of phosphorus in the surface layer after much of it has been used by phytoplankton in early summer. We sampled epilimnetic total phosphorus by collecting 2 water samples from a depth that corresponded to roughly 25% of surface light intensity, or 1/2 of the thermocline depth with a Van Dorn bottle. We measured hypolimnetic total phosphorus by collecting 2 water samples from within 3 m of the lake bottom with a Van Dorn bottle. From this point on, epilimnetic and hypolimnetic phosphorus samples were treated in a similar fashion. The water sample was subsequently frozen until the time of analysis when it was thawed. We oxidized all inorganic and organic phosphorus to orthophosphate with a potassium persulfate/boric acid mixture under high pressure and temperature. We then reacted orthophosphate with molybdenum VI and antimony III in an acidic medium to form an antimonyphosphomolybdate complex. This complex was subsequently reduced with ascorbic acid to form a blue color. Lastly, we measured the absorbance by automated colorimetry at 660 nm with a Lachat$^{(r)}$ autoanalyzer and compared to calibration curves from adenosine monophosphate (AMP) standards (24, 25). We calculated the mean of each paired sample to use in our analyses.

We used chlorophyll-*a* concentration from the water column as a surrogate for algal community biomass. We estimated the mean epilimnetic chlorophyll-*a* concentration from a pair of water samples from a depth that corresponded to roughly 25% of the surface light intensity, or 1/2 of the thermocline depth. Chlorophyll-*a* was measured by filtering water samples onto 47 mm diameter, 0.7 μm GF/F filters, freezing them, and subsequently determining chlorophyll-*a* concentration fluorometrically following extraction with methanol (24, 25). Because algae larger than 25 microns are inedible to most zooplankton (26), we calculated the proportion of inedible algae (Pin) as

$$\text{Pin} = 1 - C_{25}/C_T,$$

where C_{25} represents the chlorophyll concentration ($\mu g\ L^{-1}$) in water prefiltered through 25 μm filter, and C_T is the total chlorophyll concentration ($\mu g\ L^{-1}$) from a parallel sample that was not prefiltered.

We used a randomization procedure (27) to test for statistically significant differences in water quality parameters among the 3 human development categories (septic, sewer, and undeveloped). For each pairwise comparison between development categories for a given water-quality parameter, D_o was calculated as the observed difference in the means of the 2 categories. The randomization procedure was used to test the null hypothesis that D_o was obtained from a random ordering of the data between the 2 development categories. To achieve this, we randomly reallocated (with replacement) all of the observations to 2 categories with sample sizes n_1 and n_2 corresponding to the observed sample sizes. The value D_r was calculated as the difference in the means of the 2 randomized samples. We calculated 10^5 estimates of D_r to generate a randomization distribution for the test statistic. We then calculated the proportion of values of D_r that were at least as large as D_o to evaluate the null hypothesis of no difference between the 2 categories. We established that the observed differences between the development categories were statistically significant if less than 10% of the values of D_r were D_o. We also tested the relationships between $\log_{10}$ transformed phosphorus and chlorophyll-*a* concentrations and other lake descriptors such as local shoreline development with Pearson's linear correlations.

To further address the likelihood of a lake being eutrophic, we categorized lakes as eutrophic (> 6 $\mu g\ L^{-1}$ chlorophyll-*a*) according to previously published categories based on chlorophyll-*a* concentrations (28). We ran Chi-square goodness of fit tests to examine if the 3 lake classes (septic, sewer, and undeveloped) were equally likely to be eutrophic. All statistical analyses were performed using SYSTAT 9.0 or MATLAB 5.3 software.

RESULTS

We investigated eutrophication in lakes in the greater Seattle area, including King, Snohomish, and Skagit counties (Fig. 1). The lakes we surveyed span a full range of residential shoreline development intensities (Fig. 2A), ranging from highly developed lakes near the urban center, to lightly developed lakes at the urban-rural fringe. Lakes with houses on sewer systems occurred at the interior of the city, while lakes with homes on septic systems tended to occur at the urban-rural fringe (Fig. 1). Thus, although our development categories were based on waste management, (sewer, septic, and undeveloped) they were in effect 3 categories of spatial location in relation to the urban center: urban lakes, lakes at the urban fringe, and undeveloped lakes. In addition, lakes with homes on septic systems spanned a larger range of shoreline development, with 5% to 100% of their shoreline covered by development (Fig. 2B), than lakes with homes on sewer systems (48%–100%) that tended to only have high levels of shoreline residential development (Fig. 2C).

If local development intensity controlled eutrophication, we would expect phosphorus and chlorophyll-*a* concentrations to be positively correlated with shoreline development. If all study lakes (septic, sewer, and undeveloped) are statistically examined; development was correlated with $\log_{10}$ hypolimnetic total phosphorus (r = 0.446; n = 22; P = 0.037), but development not correlated with $\log_{10}$ chlorophyll-*a* ($r = 0.163$; $n = 25$; $P = 0.437$). However, if only the developed lakes (septic and sewer) are statistically examined, there is no significant correlation between lake shoreline development and $\log_{10}$ hypolimnetic total phosphorus ($r = -0.205$; $n = 18$; $P = 0.416$) and development and $\log_{10}$ chlorophyll-*a* ($r = -0.259$; $n = 21$; $P = 0.256$) (Fig. 3). The undeveloped reference lakes had lower levels of phosphorus (Fig. 4) and lower levels of chlorophyll-*a* (Fig. 5) than both types of developed lakes (septic and sewer), which suggests that the presence of development does increase eutrophication levels, but not in a linear fashion (Fig. 3).

An alternate hypothesis to account for the variation in indicators of eutrophication among lakes is that the method of sewage treatment determines the level of degradation of water quality. If this hypothesis is true, then lakes with septic systems would tend to have higher levels of eutrophication, as indicated by increased levels of chlorophyll-*a*, phosphorus, and the proportion of inedible algae. Lakes with shoreline septic systems had concentrations of hypolimnetic phosphorus that were 108% higher than lakes with sewer systems ($P < 0.1$) and 602% higher than undeveloped lakes ($P < 0.001$) (Fig. 4A). In addition, lakes with sewer systems had hypolim-

Figure 2. The distribution of the shoreline development (%) for all of the surveyed lakes (A); lakes with houses on septic systems (B); and lakes with homes on sewer systems (C).

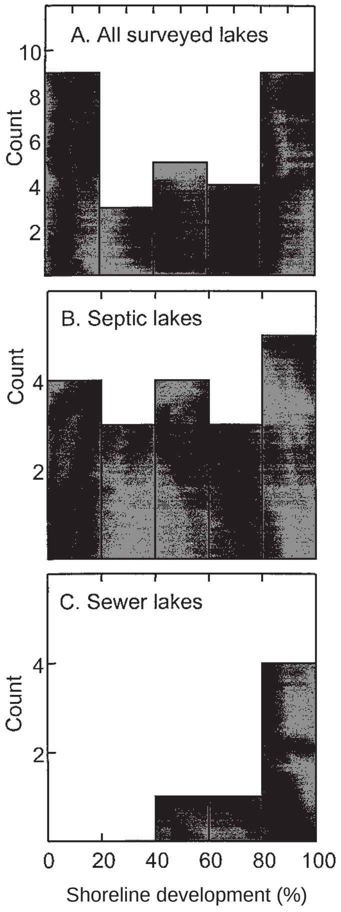
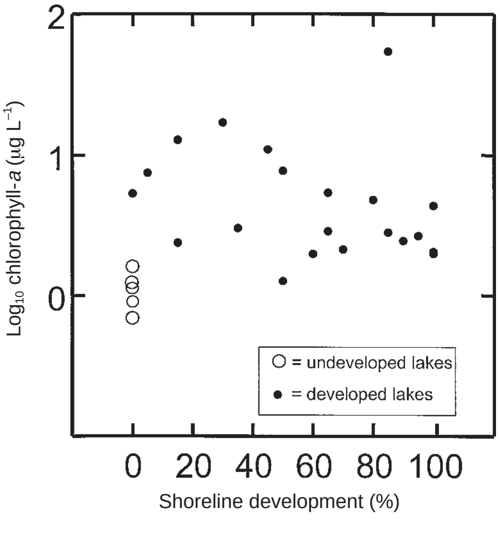


Figure 3. The relationship between the shoreline development (%) and the $\log_{10}$ amount of epilimnetic chlorophyll-*a* ($\mu g\ L^{-1}$). The filled circles represent developed (sewer and septic) lakes, while the open circles represent the undeveloped (reference) lakes.



netic phosphorus concentrations 238% higher than undeveloped lakes ($P < 0.001$).

Lakes with shoreline septic systems had concentrations of epilimnetic phosphorus that tended to be higher (47%) than lakes with sewer systems ($P = 0.12$) and were 273% higher than undeveloped lakes ($P < 0.01$) (Fig. 4B). In addition, sewer lakes had epilimnetic phosphorus concentrations 154% higher than undeveloped lakes ($P < 0.01$). Epilimnetic phosphorus concentrations were positively correlated to hypolimnetic phosphorus ($r = 0.61$; $n = 27$; $P = 0.001$). Lakes with septic systems also had chlorophyll-*a* concentrations in the epilimnion that were 174% higher than lakes with houses on sewer systems, ($P < 0.1$) and 758% higher than undeveloped lakes ($P < 0.05$) (Fig. 5A). Sewer lakes had chlorophyll-*a* concentrations 213% higher than undeveloped lakes ($P < 0.05$) (Fig. 5A). Lakes with septic systems also had proportions of inedible algae that were as high as sewer lakes ($P = 0.21$), and 214% higher than the undeveloped lakes ($P < 0.01$) (Fig. 5B). Sewer lakes had proportions of inedible algae that were 155% higher than undeveloped lakes ($P < 0.01$) (Fig. 5B).

We further categorized lakes as generally eutrophic or non-eutrophic based on chlorophyll-*a* concentrations. Although there is variation in the threshold levels for defining when a lake is eutrophic (28–30), we classified the lakes as eutrophic based on one such published categorization (28). Based on this categorization 37% of the septic lakes were eutrophic if classified by chlorophyll-*a* concentrations, while none of the sewer lakes or undeveloped lakes met the criteria for being eutrophic. Septic lakes are more likely to be eutrophic than both undeveloped lakes and sewered lakes if based on chlorophyll-*a* categorization ($\chi^2 = 4.65$; df = 2; $P < 0.10$).

DISCUSSION

Phosphorus is the nutrient that is most often limiting to phytoplankton in North American lakes (7) and hence is the nutrient that most tightly controls productivity and eutrophication (8). Hypolimnetic and epilimnetic phosphorus concentrations were higher in septic lakes than sewer and undeveloped lakes (Fig. 4). We believe that phosphorus levels are higher in the septic lakes because of nonpoint source pollution associated with waste treatment. Because septic lakes were located along the urban fringe (Fig. 1), this result suggests that these lakes have higher levels of phosphorus. In addition, because sewer lakes have higher levels of shoreline development than septic lakes (Fig. 2), higher levels of phosphorus in septic lakes suggest that the amount of local shoreline development does not directly affect the degree of eutrophication of urbanized lakes.

Septic lakes had the highest levels of phytoplankton biomass, as indicated by levels of chlorophyll-*a* (Fig. 5A), which is an additional indication that lake eutrophication is greatest at the urban fringe. This provides further evidence that the type of development is more important than the amount of shoreline development for controlling eutrophication. Thus, lakes with houses on septic systems generally have a higher standing crop of phytoplankton than undeveloped lakes or lakes with houses on sewer systems. As algal biomass increases, water transparency decreases, the photic zone shrinks, there is increased shading of the benthic zone and an increased anoxic region (9). Although there can be top-down control of the standing crop of phytoplankton by grazers (31–33), the observed differences in chlorophyll-*a* between the lakes are probably not due to trophic cascades since all of the lakes have similar top predators, and there was no systematic differences in zooplankton communities among development categories. We attribute differences in chlorophyll-*a* to differences between the levels of phosphorus in lakes, as lakes with higher levels of phosphorus also had higher levels of chlorophyll-*a* ($r = 0.603$; $n = 27$; $P = 0.001$).

Another biological symptom of eutrophication in lakes with septic systems was an increase in the proportion of inedible al-

Figure 4A. The relationship between the type of shoreline development and the amount of hypolimnetic total phosphorus (μg L^{-1}).
Figure 4B. Relationship between lakeshore development type and the amount of epilimnetic total phosphorus (μg L^{-1}). The filled circle labeled ”59” represents a septic lake whose epilimnetic total phosphorus was 59 μg L^{-1}. The central horizontal line represents the median value, and the upper and lower hinges of the boxes denote the interquartile range. The whiskers contain the range of values that are within 1.5x the interquartile range. Values that lie outside of that range are represented by solid circles.

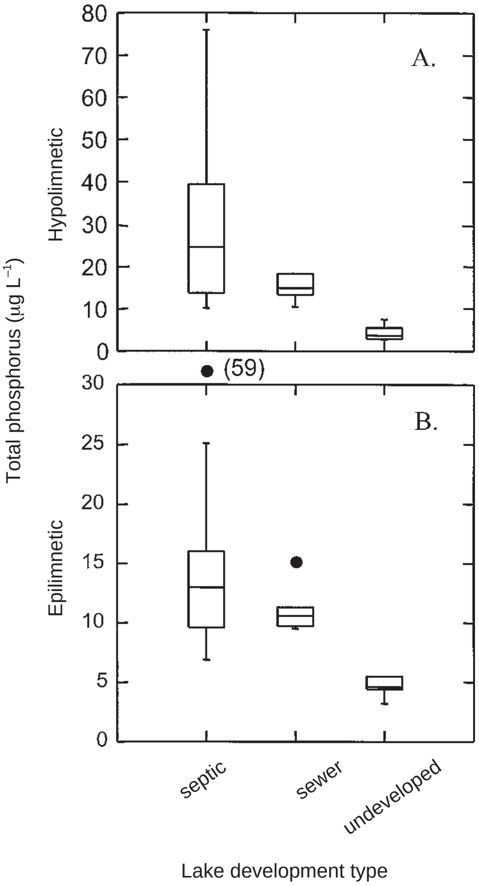
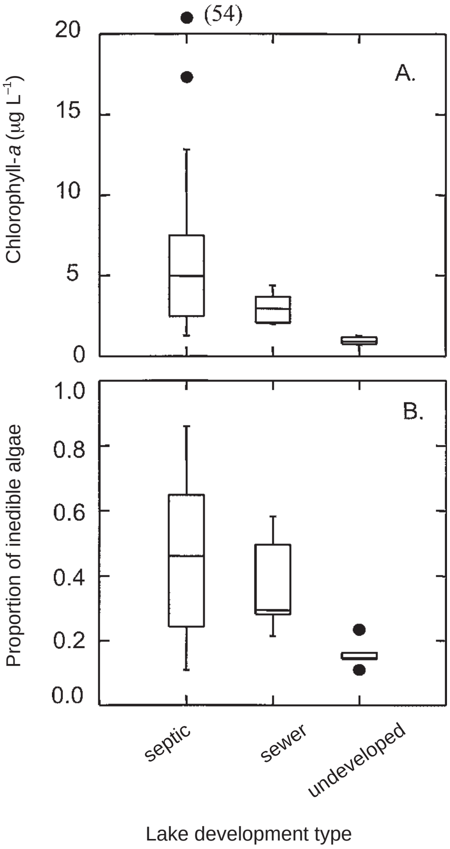


Figure 5A. The type of shoreline development and the amount of chlorophyll-*a* (μg L^{-1}). The filled circle labeled “54” represents a septic lake whose chlorophyll-*a* level was 54 μg L^{-1}.
Figure 5B. Relationship between lakeshore development type and the proportion of inedible algae. (See Fig. 4 for an explanation of the plot).



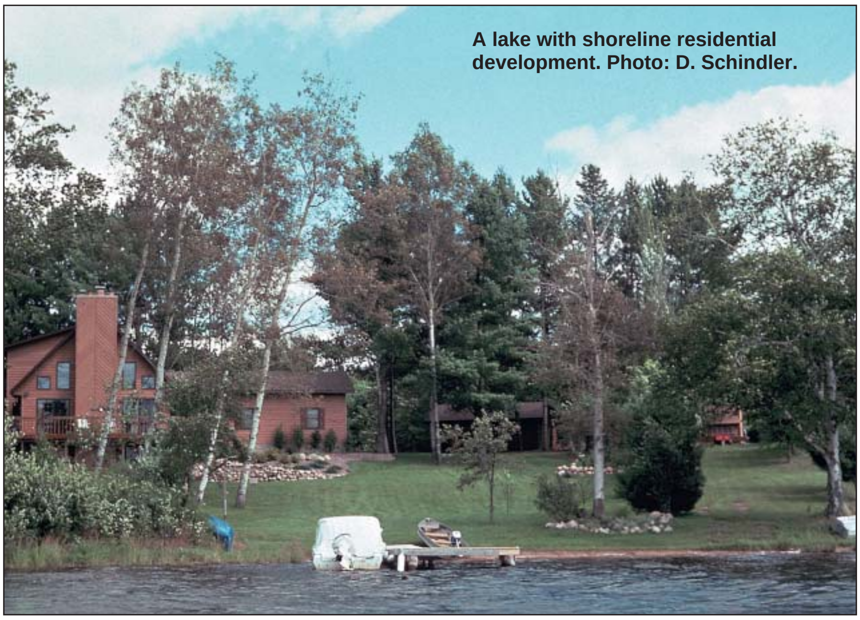
gae (Fig. 5B). Septic system lakes tended to have a higher proportion of inedible algae than lakes with sewer systems or undeveloped lakes. At higher phosphorus levels, the algal community often shifts to the larger blue-green algae that often dominate the community due to their N_2 fixing capabilities (7). Lakes with more hypolimnetic phosphorus also had higher levels of ungrazable algae ($r = 0.571$; $N = 24$; $P < 0.01$). Thus, because septic lakes have higher levels of phosphorus, they had higher levels of inedible algae (Fig. 3). These large algae are often blue-green algae, and some species can be toxic if ingested by humans or pets (10, 11).

Lakes with houses on septic systems were more likely to be eutrophic than both sewered lakes and undeveloped lakes when classified based on the levels of chlorophyll-*a*. Because septic lakes generally occurred at the urban-rural fringe (Fig. 1), this result also shows that these lakes are more likely to be eutrophic than urban lakes.

Thus, septic lakes tended to have higher levels of all measured indicators of eutrophication (phosphorus, chlorophyll-*a*, and the proportion of inedible algae) than lakes with houses on sewer systems and undeveloped lakes (Figs 4, 5). In addition, the septic lake category had the most variance in the eutrophication parameters (Figs 4, 5). This variability is probably due to the inherent variability in our classification scheme. The septic lake category is composed of any lake that has one or more houses on septic systems, and ranges from highly developed lakes to undeveloped lakes, and theoretically contains lakes with only one septic system, as well as lakes with numerous septic systems. It is also possible that variance is increased because of individual differences in the performance of septic fields in retaining phosphorus from the sewage or because eutrophic lakes are inherently more variable than less productive systems.

There have been many demonstrated cases of septic system pollution of our inland waters as a result of septic system failure due to over-saturation of the soil or failures of the septic tank. Septic systems have been found to pollute groundwater with fecal coliform bacteria (34, 35), nitrate (15, 34, 36–39), phosphate (34, 38, 40), alkalinity (39, 41), acidity (36, 39), and many diseases, including hepatitis A, gastroenteritis, and others (for review, see 42). It is likely that septic systems have contributed to the eutrophication of lakes at the urban-rural fringe in the greater Seattle region.

Although these results suggest that septic systems are a significant source of phosphorus and the cause of lake eutrophication in the Seattle area, there are other possible mechanisms for this result. Perhaps other nonpoint sources of pollution that are associated with the urban fringe are the major contributing source of phosphorus. Several previous studies have attributed eutrophication to phosphorus pollution from agricultural runoff (16, 19, 21, 22, 43). It is possible that agriculture might be contributing to eutrophication along the urban-rural fringe of the Seattle. However, the amount of agriculture in the drainage basin in 1976 (23) was not correlated to the current levels of $\log_{10}$ chlorophyll-*a* ($r = -0.229$; $n = 24$; $P = 0.282$) or $\log_{10}$ phosphorus ($r = 0.231$; $n = 20$; $P = 0.328$). In general, agriculture made up a low percentage of the historical lake drainage basin for both septic lakes (mean = 9.8%, SE = ± 8.6%) as well as sewer lakes (mean = 7.2%, SE = ± 2.0%). Other explanations for the pattern of eutrophication along the urban fringe that we could not statistically examine include various nonpoint nutrient pollution sources associated with high rates of development such as runoff from lawn fertilizers, soil disturbance, construction sites, or waste from pets or waterfowl (6).



A lake with shoreline residential development. Photo: D. Schindler.

MANAGEMENT IMPLICATIONS

In the Seattle region, lakes along the urban-rural fringe had levels of eutrophication that were at least as high as urban lakes. In addition, lakes with shoreline homes on septic systems had higher levels of eutrophication than lakes with shoreline homes on sewer systems. Our results should be somewhat encouraging, because they suggest that control of nutrient pollution in the urban centers has been somewhat effective. Over time, lakes generally proceed from being developed by houses on septic systems to being developed by sewer systems. However, because sewer lakes were less eutrophic than septic lakes, these results suggest that lakes do recover to some extent from previous nutrient pollution. However all developed lakes had reduced water quality conditions as compared to the undeveloped lakes in our study, thus suggesting that recovery is not complete (Figs 4, 5).

Because we observed the most severe eutrophication at the urban fringe, it is apparent that development is increasing faster than the infrastructure and regulations needed to control nonpoint source pollution. Although we were unable to isolate the mechanism for this pollution, it is likely that septic system failure is contributing to water quality degradation. It is possible that more rigorous enforcement of regulations or stricter regulations of septic systems would decrease the amount of lake eutrophication at the urban fringe. However, it is also possible that even a properly working septic system does not deal with waste effectively enough to prevent nutrient pollution. Septic system pollution could be minimized by installing sewer systems in anticipation of future residential development of lakeshores or by requiring sewage systems to be installed for all future developments. Although this solution might be initially costly, it is likely to be economically beneficial in the long-term, as non-eutrophic lakes have higher economic values than their eutrophic counterparts (12, 13, 44).

Although eutrophication can sometimes be reversed by reducing phosphorus inputs, it is often a lengthy and costly process which can require dredging of nutrient laden soils, chemical treatment, biomanipulation, or regulation of phosphorus inputs to extremely low levels for an extended period of time, and success rates are extremely variable (9, 45). Thus, it is potentially much easier to preemptively avoid eutrophication than to attempt restoration of eutrophic lakes.

The causes of lake eutrophication vary across large spatial scales in response to different types of land use, land cover and geologies (46). For example, in the midwest United States the soil is rich in nutrients and agriculture is a major component of the landscape. Not surprisingly, in this region many studies have found runoff from agriculture to be the principle cause of eutrophication (16, 20–22). In contrast, our study in the Seattle area, a landscape that has high levels of residential development and low levels of agricultural use, suggests that lake eutrophication is worst along the urban fringe probably due to septic system pollution on lakeshore homes. This is additional evidence that the threat of eutrophication needs to be recognized as being highly variable across landscapes, and addressed on a regional or local basis (46). The urban-rural fringe is likely to be the site of high level of eutrophication in regions with high levels of urbanization, high regulations of point sources of pollution, but poorly regulated residential development.

CONCLUSION

Even though freshwater represents a tiny proportion of the global landscape, it is arguably the most valuable and sought-after resource on earth (13). Our study suggests that the urban fringe is where freshwater lakes in the Seattle region are being eutrophied most heavily, as indicated by higher levels of chlorophyll-*a*, phosphorus, and the proportion of inedible algae. Lakes at the urban-rural fringe probably have the highest levels of eutrophication because of septic system pollution and, contrary to expectations, the areas with highest human densities do not necessarily have the highest levels of lake eutrophication.

The Seattle area is familiar with eutrophication. Lake Washington in urban Seattle was restored from a eutrophic status by pollution regulations inspired by a grassroots environmental movement, perhaps the most famous lake restoration success story (17). Our study shows that the Seattle area needs to continue to address eutrophication as a serious threat to freshwaters. As many developed regions have reduced point sources of nutrient pollution, there is a need to expand pollution control to include nonpoint sources of pollution. As urban areas continue to grow and the urban boundaries expand, more lakes will be threatened by eutrophication at the urban-rural fringe. Development should to be managed more stringently to minimize the nutrient pollution contaminating lakes along the urban fringe.

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Jonathan W. Moore is a graduate student of aquatic ecology in the Department of Zoology, University of Washington. Daniel E. Schindler, professor, also studies aquatic ecology in the same department. Their address: Department of Zoology, University of Washington, Box 351800, Seattle, WA 98195, USA.
E-mail: jwmoore@washington.edu

Mark D. Scheuerell is a post-doctorate researcher at the School of Aquatic and Fisheries Sciences, University of Washington. Danielle Smith is an undergraduate student at the same university. Their address: University of Washington, Box 351800, Seattle, WA 98195, USA.

Jonathan Frodge is a research scientist for King County. His address: King County Water and Land Resources, 201 South Jackson St, Suite 600 Seattle, WA 98104-3855, USA.