

# Soil Phosphorus Concentrations in Dane County, Wisconsin, USA: An Evaluation of the Urban–Rural Gradient Paradigm

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**ABSTRACT** / Understanding the magnitude and location of soil phosphorus (P) accumulation in watersheds is a critical step toward managing runoff of this pollutant to aquatic ecosystems. Here, I examine the usefulness of urban–rural gradients, an emerging experimental design in urban ecology, for predicting extractable soil P concentrations across a rapidly urbanizing agricultural watershed in southern Wisconsin. I compare several measures of an urban–rural gradient to predictors of soil P such as soil type, slope, topography, land

use, land cover, and fertilizer and manure use. Most of the factors that were expected to drive differences in soil P concentrations were found to be poor predictors of Bray-1 (extractable) soil P, which ranged from 4 to 660 ppm; while there were several significant relationships, most explained only a small proportion of the variation. A multiple linear regression model captured approximately 37% of the variation in the data using the urban–rural gradient, topography, land use, land cover, manure use, and soil type as predictors. There was a significant relationship between Bray-1 P concentration and each of the urban–rural gradients, but these relationships explained only between 2.6% and 3.3% of the variation in P concentrations. Extractable P concentration in soils, unlike some other ecosystem properties, is not well predicted by urban–rural gradients.

Phosphorus (P), a key pollutant responsible for eutrophication of aquatic ecosystems, is accumulating in the soil of many agricultural watersheds around the world (Tunney 1990, Bennett and others 2001). Soil P, which moves downhill into aquatic systems sorbed to eroded soil particles and dissolved in surface runoff and groundwater, is an important consideration for management of eutrophication. Soil P sets the stage for future P runoff and management because it changes more slowly than other factors that determine eutrophication, such as P in lake water or sediments (Reed-Andersen and others 2000). The amount and pattern of P accumulation is likely to play a key role in determining the amount and timing of P runoff to aquatic systems (Heckrath and others 1995). Therefore, understanding the magnitude and location of soil P accumulation and storage is a critical step toward limiting the runoff of this nutrient to freshwater ecosystems.

Because it is impractical to measure soil P in every location around a watershed, models are needed for predicting soil P concentrations. Land use is one im-

portant predictor of soil P concentrations (Arbuckle and Downing 2001, Frink 1991, Beaulac and Reckhow 1982, Jordan and others 1997). However, land use alone is unlikely to capture the full variability of soil P concentrations in an area because it does not account for differences in current land management or historical use and management. Urban–rural gradients, an emerging experimental design in urban ecology, may be a useful predictor of soil P because such gradients can integrate land use, land management, and historical land use and management. Additionally, study of urban–rural gradients may lead to a better understanding of the factors that control soil P concentrations in agricultural watersheds undergoing urbanization.

Much like studying trends in species distribution along gradients of moisture or elevation, changes in ecological response along a gradient of human use and management may be informative. Because gradients have offered useful insights on spatial variability for understanding diverse ecological systems across a wide range of controlling factors (McDonnell and Pickett 1993, Whittaker 1967), application of this tool to investigate cities makes sense. Additionally, studying changes along gradients can be useful for understanding the effects of multiple stressors, such as those found in urban ecosystems (Breitburg and others 1998). It is, however, generally more difficult to quantify gradients of land management than of moisture or elevation.

**KEY WORDS:** Phosphorus; Eutrophication; Urban–rural gradient; Urban ecology; Soil

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Therefore, it is likely to be difficult to develop a uniform gradient approach that is effective in many cities for a wide range of variables.

Urban–rural gradients have generated much excitement since their initial use in the early 1990s (McDonnell and Pickett 1993, Pickett 1997, Grimm and others 2000). Because they explicitly include people, urban–rural gradients may be useful not only for answering fundamental questions about urban ecosystems, but also for addressing applied problems of anthropogenic influence (McDonnell and Pickett 1991). Urban–rural gradients can be designed to integrate the many individual factors that make up the process that we call “urbanization.”

The use of urban–rural gradients as predictors of environmental factors has been based on the observation that some urban landscapes are characterized by a highly developed urban core surrounded by irregular rings of diminishing anthropogenic influences (Berry 1991). The assumption behind this use of urban–rural gradients is that distance from the center of development represents a gradient from high to low intensity of human impact upon many variables of interest. Following this assumption, most urban–rural gradient studies have been completed in cities that have a core urban area surrounded by suburbs and then by park land or other primarily unused land. Many other cities are surrounded by agricultural areas rather than by unimpacted land. A critical step in the development and use of urban–rural gradients in ecology will be determining if urban–rural gradients are useful predictors in cities with different spatial patterns, such as those surrounded by agriculture. A gradient from urban center to agricultural periphery may represent strong differences in fertilizer use and therefore soil P. This hypothesis is tested in the study presented here.

Studying the effect of urban areas and urbanization on upland P may provide an important missing link to our understanding of the impact of upland soil P on lake ecosystems. While the role of agricultural management in nonpoint source pollution has been relatively clearly defined, there is less information on the interaction of urbanization and agriculture on nonpoint source pollution (Sharpley and Tunney 2000).

Here, I use urban–rural gradients to examine soil P storage in Dane County, Wisconsin, USA and to assess the value of urban–rural gradients as explanatory and potentially predictive research tools. I use the urban–rural gradient as an approach for integrating across many factors that I expect to influence soil P concentrations, such as land use, land management, and historical legacies of land management. I further aim to evaluate the robustness of the urban–rural gradient

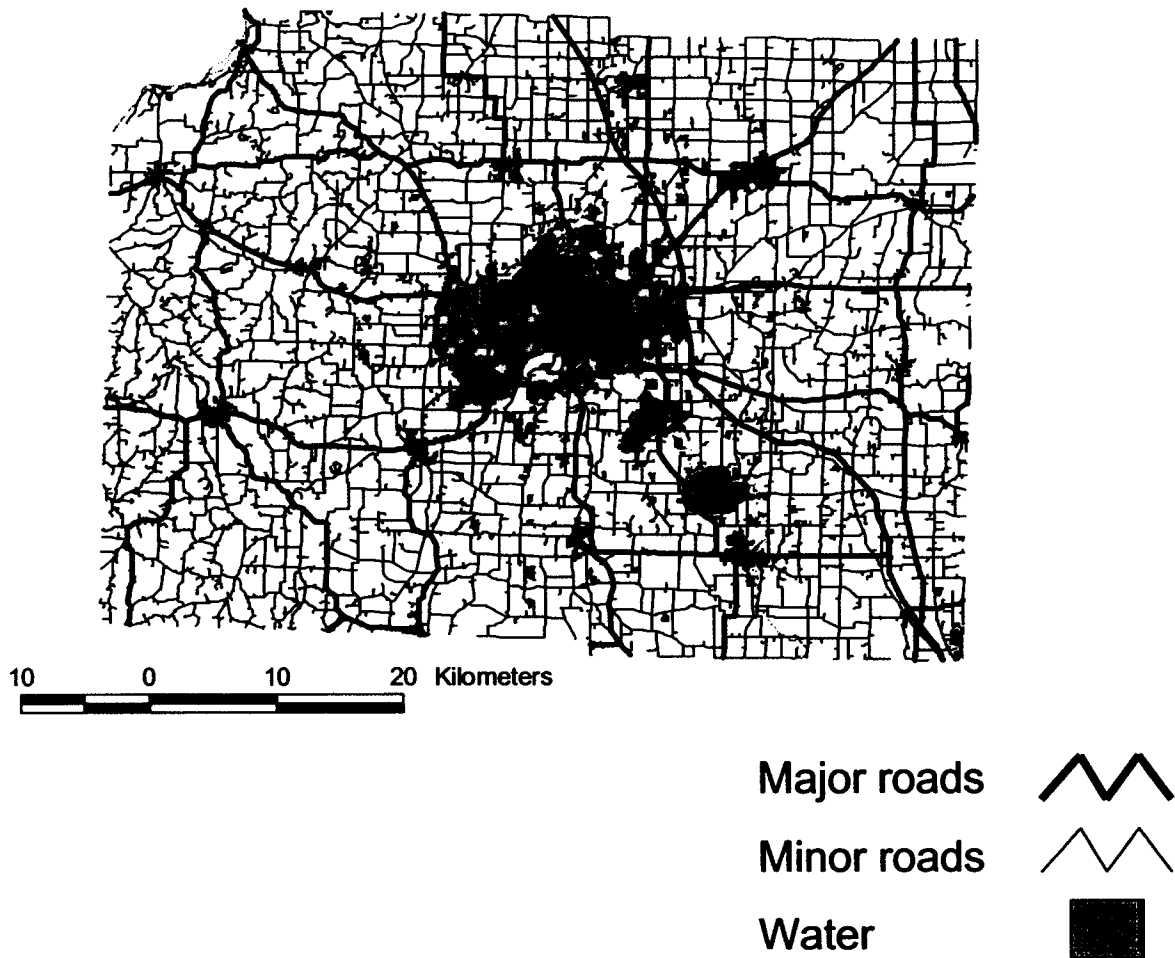
concept by analyzing data using several different quantitative measures of the gradient.

Many factors play a role in soil P accumulation and storage, including parent material (Tunney and others 1997); land use and land cover (Frink 1991, Beaulac and Reckhow 1982, Jordan and others 1997); land management, including fertilizer use and manure application (McCollum 1991, Sharpley and others 1996); and historical land use and management (McCollum 1991). I hypothesize that many of these factors change in a consistent manner across an urban–rural gradient in Dane County and that consequently soil P concentrations might also change along the gradient. For example, there may be more farms and therefore higher fertilizer use at the rural end of the gradient. Newly developed areas, with large, new lawns, might receive more fertilizer than smaller urban lawns. Taken together, these considerations lead to a prediction of a range of P inputs to the land from very high in agricultural areas to very low in urban areas.

Because P in the soil changes slowly, historical land use and management should also have a substantial impact on soil P. I expected the magnitude of this impact to change along the urban–rural gradient, such that lawns closer to the rural end of the gradient (newer homes), which are likely to have been farmed more recently, might have higher P concentrations. Lawns in urban areas, on the other hand, would have had about 100 years to recover from the legacy of intensive agricultural use and might therefore have lower P concentrations in the soil. Additionally, historical nutrient additions to urban lawns that were farmland 100 years ago would have been much lower than the nutrient additions on lawns that were farmland just 20 years ago. Other factors that might influence soil P, such as slope, percent cover by vegetation, and topography are not expected to change across this urban–rural gradient.

This urban–rural gradient was developed primarily to capture changes across a historical legacy of land use and management as well as current land use and management. I created a definition and map of an urban–rural gradient as a multidirectional gradient representing the relative degree of transition from agricultural to urban land, not as a fixed or linear transect on the landscape. It was designed to aggregate the impacts of land use and management factors with historical patterns of land use into a testable framework.

Specifically, I ask: (1) how do potential indicators of soil P concentrations vary along the urban–rural gradient I developed; (2) do statistically significant relationships exist between these indicators and the urban–rural gradient; (3) do statistically significant



**Figure 1.** Map of Dane County showing major and minor roads, urbanized areas, and the location of the Madison area lakes.

relationships exist between these indicators and soil P concentrations; and (4) does a statistically significant relationship exist between soil P concentrations and the urban–rural gradient?

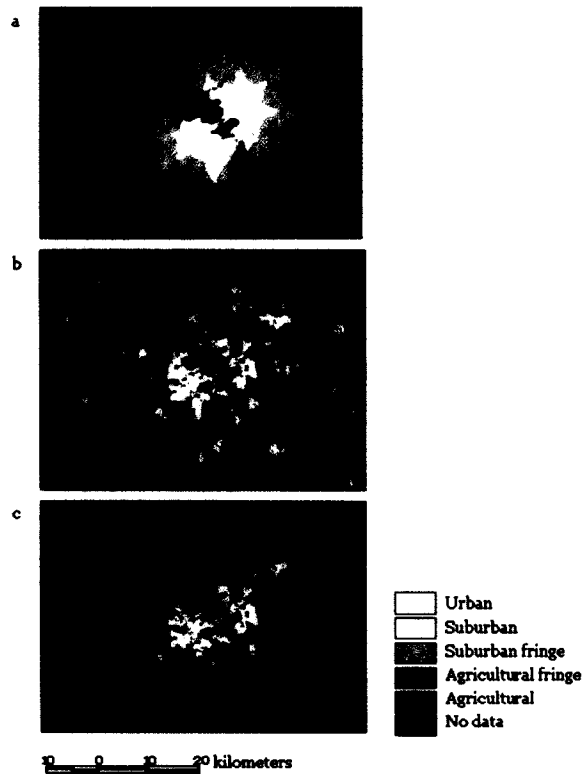
### Methods

This study was completed in Dane County, a 310,250-ha area located in south-central Wisconsin, USA. The climate of Dane County is generally long, cold winters and warm, humid summers. The average annual rainfall is 77.2 cm, falling primarily in the months of May through September. The soils are primarily Mollisols and Alfisols (USDA 1978).

Dane County, Wisconsin (population: 426,526) was first settled in the early 1800, and is primarily an agricultural area, with one large city (Madison, population: 208,054) and several smaller surrounding cities and towns (Figure 1). The agricultural land in the area is a

mixture of cropland (mostly feed corn and soybeans) and relatively small livestock and dairy operations. The average farm size in Dane County is 73 ha (Dane County Regional Planning Commission 1998). Dane County is also a rapidly urbanizing area: about 1323 ha of farmland are developed into suburban uses annually (Dane County Regional Planning Commission 1998).

Although many urban–rural gradient studies have been conducted along a unidirectional gradient from the urban center outward, this approach is ill-suited for a study in Dane County for several reasons. First, many gradient studies revealed nonlinear relationships between the response variables and the distance gradient, indicating that urbanization-related changes are not always correlated simply with distance from the urban core alone (Medley and others 1995). Furthermore, the pattern of land use and development in Madison is highly influenced by the position of the Madison chain of lakes. In this geographical setting, linear distance



**Figure 2.** Three maps based on three definitions of urban–rural gradient for Dane County, Wisconsin, USA. Although the gradient is continuous in all cases, the map has been divided into 5 zones. These zones are: urban, suburban, suburban fringe, agricultural fringe, and agriculture. (a) The urban–rural gradient as defined by modified distance (analog for driving time to the capitol). The X in between the northernmost lakes marks the location of the state capitol building. (b) The urban–rural gradient as defined by population density. This map is calculated based on block group level data from the US Census Bureau. (c) The urban–rural gradient defined as a combination of the population density and modified distance maps. It is a multiplicative combination of the other two maps.

gradient results would be highly dependent on the direction of the transect away from the city center. A gradient that includes development patterns and population density would more effectively integrate factors believed to control soil P concentrations.

I created three maps of Dane County depicting several different definitions of an urban–rural gradient. These included a gradient based on a modified version of distance from the urban center (Figure 2a), a population density-based gradient (Figure 2b), and a combination of the population density and modified-distance gradient (Figure 2c). The modified-distance gradient is an attempt to define a gradient as similar as

possible to the distance method used in other studies, while incorporating Dane County’s unique geography. Because urban and suburban development in Dane County appear to follow a pattern along major roads, I used an analog for driving time to the center of downtown (marked by the state capitol building) as a modified distance gradient. Population density was chosen because it may be a representation of neighborhood type, land use, and age of the development—all factors I hypothesized would play an important role in determining soil P concentrations.

Maps of Dane County urban–rural gradients were created based on information available from local sources. Population density and housing density information was available from the Applied Population Lab in the Rural Sociology Department at the University of Wisconsin–Madison (<http://www.ssc.wisc.edu/poplab/>) and from the US Census homepage (<http://www.census.gov/>). Also available from the Applied Population Lab were digital maps of the location of census blocks and block groups. Digital maps of the city of Madison, the location of the capitol building, and major and minor roads were available from the Land Information and Computer Graphics Facility at the University of Wisconsin–Madison ([http://www.lic.wisc.edu/pub/licgf\\_data\\_sets.htm](http://www.lic.wisc.edu/pub/licgf_data_sets.htm)). The Land Information and Computer Graphics Facility also provided digital maps of parcel location and associated data such as ownership, land use, and zoning from the city of Madison and Dane County.

Maps were designed using ArcView GIS software. Although the gradients remained continuous, they were always divided into five zones: urban, suburban, suburban fringe, agricultural fringe, and agricultural. Resolution of land use into five zones facilitated measuring differences among urban–rural gradient definitions and enhanced the visual interpretation of the maps.

The map of the urban–rural gradient using a modified measure of distance from the capitol (the modified-distance map, Figure 2b) was developed with a grid size of  $100 \times 100$  m. The location of the capitol was marked. The driving time to the capitol building was calculated by summing the cost of moving across the grid from one cell to the next in the direction of the capitol building: low cost along major roads, medium cost along minor roads, and high cost for moving from a grid cell with no roads towards the nearest road. The cost for moving from every  $10,000 \text{ m}^2$  grid cell to the capitol was calculated based on this algorithm and mapped. Total cost, normalized to vary between 0 and 1, is considered to be the urban–rural gradient value. This continuous gradient was divided into zones for mapping purposes. The five urban–rural gradient

zones were determined by standard deviation of the gradient. Any grid cell between 3 and 2 standard deviations below the mean gradient value was considered to be urban. Any grid cell with a value between 2 and 1.5 standard deviations below the mean was suburban. Similarly, between 1.5 and 1 standard deviations below the mean was considered suburban fringe, 1 to 0.5 standard deviations below the mean was agricultural fringe, and from 0.5 standard deviations below the mean to 3 standard deviations above the mean was called agricultural. Grid cell values were then rescaled to range between 0 and 1, with 1 being at the state capitol building and 0 being the cell with the longest travel time to the capitol.

Population density data were available from the census web page by census block. Coverages were reclassified to a 100 × 100 m grid by averaging the population density values for all census blocks (weighted by area) within each cell. Zone was determined for each grid cell: any cell with a population of  $\geq 2687$  people/km<sup>2</sup> was classified as urban, of 1737–2687 people/km<sup>2</sup> as suburban, of 750–1736 as suburban fringe, of 25–749 as agricultural fringe, and  $\leq 24$  people/km<sup>2</sup> as agricultural. These numbers match closely with the U. S. Census definition of urban core areas, which is approximately 2590 people per square kilometer (<http://www.census.gov>). The grid cell values were then rescaled to range between 0 and 1, with 0 being the lowest population density and 1 being the highest.

A combination map, consisting of the information in both the population density map and the modified-distance map, was also created (Figure 2c). This map is simply based on a grid cell by grid cell multiplication of the reclassified values from the population density and the modified distance map. In this paper, I will refer to this map as the combination map.

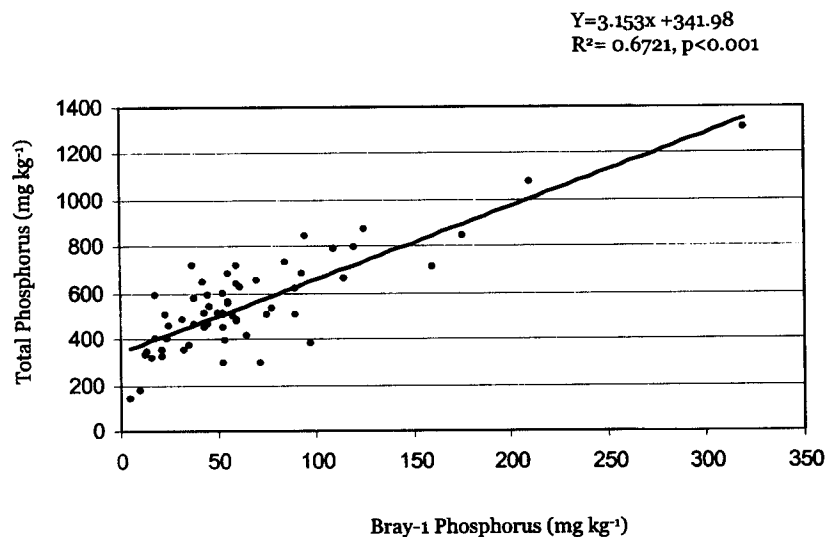
Data points for measuring soil P and associated factors were stratified by zone and randomly located within each zone according to the combination map—with approximately 70 data points per zone. Location and address of each point were determined using the Madison and Dane County parcel GIS layers. Permission was requested from landowners to take a soil sample, and the precise location of the sample on the property was determined using standard randomizing techniques. If permission was denied (2 cases out of 330) or if there was no one present at the location, a coin toss was used to determine movement one parcel to the right or to the left along the same road. Landowners were also asked about their fertilizer use practices, manure use, dog ownership, and the date the house was built, if known.

Approximately 400 soil samples were taken in the top soil horizon to a depth of 13.5 cm with a standard

soil corer (diameter = approximately 1.6 cm). This depth was always within the surface horizon and any grass thatch was removed from lawn samples. Other data collected include percent slope, convex or concave nature of the slope, land use, land-cover type, and percent vegetative cover. The visually perceived zone was also recorded. The visually perceived zone was determined by visual inspection using a predetermined set of definitions of each zone. For example, urban sites were those with the highest housing density or some industrial use; suburban sites were those of moderate housing density and residential character; suburban fringe were newer residential developments of low housing density and larger houses; agricultural fringe were older residential developments of low density; and agricultural were those areas that were actively farmed. A handheld global positioning device was used to determine the precise ( $\pm 1$  m) location of the soil sample.

Soil samples were stored for no more than 3 weeks at room temperature before analysis. They were then dried for 15–24 hours at 50–55°C and sieved (1.8-mm mesh). Soil samples were then analyzed for Bray-1 P at the University of Wisconsin Soil and Plant Analysis Lab. Bray-1, a measure of extractable P, is a commonly used measure of phosphorus available to plants in agricultural systems. While relationships between extractable soil P and dissolved P in runoff have been noted in some systems (Sharples and others 1993, Sharples 1995), these extractions were generally developed to estimate plant available P, not to reflect P storage in the soil or P runoff. Therefore, we tested a subset (60) of our samples for total P, a better measure of P storage in soils. A regression of our samples indicates a reasonably close relationship between Bray-1 P and total P in our study area soils (Figure 3), indicating that our Bray-1 P results are probably a satisfactory estimate of both extractable P and the sorbed P that tends to accumulate in agricultural soils.

Diagnostic plots of residuals indicated that log-transformed values of Bray-1 P best met the assumptions for analysis of variance (Box and others 1978). Linear regression and ANOVA were used to determine the relationship between the various predictors and the three urban–rural gradients, between the various predictors and log soil P concentrations, and to determine the best relationship between the urban-rural gradients and log soil P concentrations (PROC GLM; SAS Institute 1995). A backwards stepwise regression procedure, with attention to the Akaike information criterion (AIC) and P-to-remove (Sokal and Rohlf 1995) was used to determine the best linear multiple regression model (PROC GLM; SAS Institute 1989–1996, Cary, North Carolina).



**Figure 3.** Relationship between Bray-1 P and total P for a subset of samples,  $R^2 = 0.67$ ,  $P < 0.001$ .

**Table 1.** Relationships between continuous predictor variables and log Bray-1 P (mg/kg)<sup>a</sup>

Variable	$R^2$	$P$	Relationship
House age	0.084	$< 0.001$	$\text{Log } [P] = 1.487 + 0.003x + \epsilon$
Percent cover	0.040	$< 0.001$	$\text{Log } [P] = 1.674 - 0.007x + \epsilon$
Slope	0.015	0.029	$\text{Log } [P] = 1.970 - 0.004x + \epsilon$

<sup>a</sup>Farms are excluded from the house age analysis because house age was considered to be a surrogate for time since a sample site was farmed.  $N = 170$ .

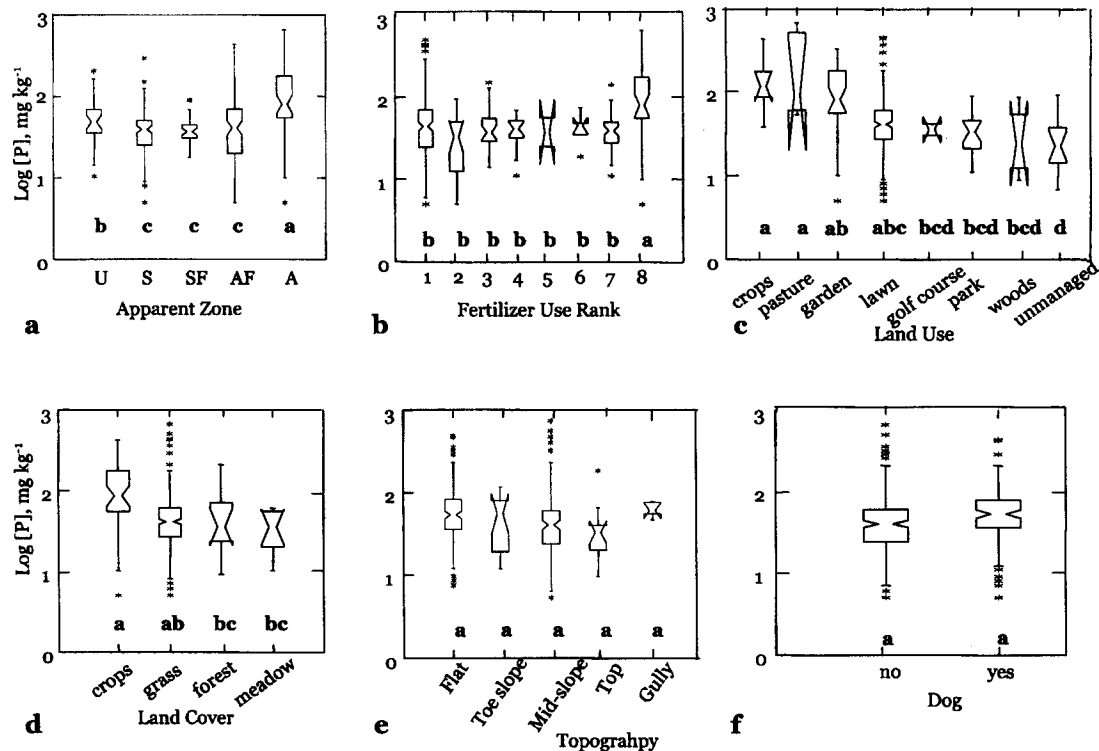
## Results

Most of the factors that were expected to drive differences in P concentrations were not found to be good predictors of Bray-1 P. Among the continuous predictors that I measured (slope, percent cover by vegetation, and house age), significant relationships were found between all three factors and log P at the  $\alpha = 0.05$  level; however, none explained enough of the variation in extractable P concentrations to be considered useful (Table 1). For example, there is a significant relationship between house age ( $P < 0.001$ , no farms included in analysis) and log P, but the relationship explains only 8.4% of the variation in extractable P concentrations.

Categorical factors hypothesized to be related to extractable soil P were also not effective predictors (Figure 4). Bray-1 P was significantly higher in the agricultural zone than in all other zones; however, all residential zones (urban, suburban, suburban fringe, and agricultural fringe) had similar P concentrations. While differences in Bray-1 P concentrations existed among some of the visually perceived zones, many had indistinguishable mean P concentrations. Specifically, extractable P concentrations were highest in sites

within the zone visually perceived to be agricultural. Second highest concentrations occurred in sites within the zone visually perceived to be urban. Zones visually perceived to be suburban, suburban fringe, and agricultural fringe all had similarly low P concentrations (Figure 4a). There were also some differences between different types of land cover and land use. For example, sites used for crop production had the highest P concentrations, followed by a group consisting of pasture, garden, woods, roadsides, and lawns (Figure 4c). The lowest extractable P concentrations were found in parks, golf courses, and unmanaged areas. Land cover followed a pattern of highest soil P concentrations in crop cover, followed by grass, forest, and then meadow cover (Figure 4d). P concentrations were indistinguishable among sites with different rates of fertilization (Figure 4b), different topographic types (Figure 4e) and between sites with and without dogs (Figure 4f).

The categorical and continuous predictor variables also did not relate closely to any of the three urban-rural gradient representations. Table 2 and Figure 5 show results for the combined gradient. Analysis with other measures of the urban-rural gradient led to similar results. The closest relationship is found between



**Figure 4.** Whisker plots of log Bray-1 P for various categorical predictor variables. The waist of the box is the median value. The notch represents the values between the 1st and 3rd quartile. The box ends mark the limit of all data except the outliers, and the stars mark the outliers. Letters below the boxes represent the results of a Wilcoxon signed-rank test. Different letters indicate those categories that have significantly different log P values. (a) Visually perceived zone versus log P. The visually perceived zone is the zone visually determined by the researcher during sampling based on a predetermined set of visual cues. U = urban; S = suburban; SF = suburban fringe; AF = agricultural fringe; and

A = agricultural. (b) Fertilizer use rank versus log P. Rank 1 is no fertilizer used; rank 2, property is almost never fertilized; rank 3, property is fertilized by owner once per year; rank 4, fertilized by owner twice per year; rank 5, fertilized by owner three times per year; rank 6, fertilized by owner four times per year; rank 7, property is professionally fertilized; rank 8, agricultural fertilizers are applied. (c) Land use versus log P. (d) Land cover versus log P. (e) Topography (local to the sample) versus log P. (f) Presence of a dog residing on the property versus log P. Yes means a dog resides on the property. No means no dog resides on the property.

**Table 2.** Relationships between combination urban-rural gradient value (URG) and continuous P predictor variables<sup>a</sup>

Variable (y)	R <sup>2</sup>	P	Relationship
House age	0.010	0.195	$y = 45.996 - 11.3(\text{URG}) + \epsilon$
Percent cover	0.010	0.069	$y = 95.329 - 6.89(\text{URG}) + \epsilon$
Slope	0.014	0.031	$y = 3.865 + 2.73(\text{URG}) + \epsilon$

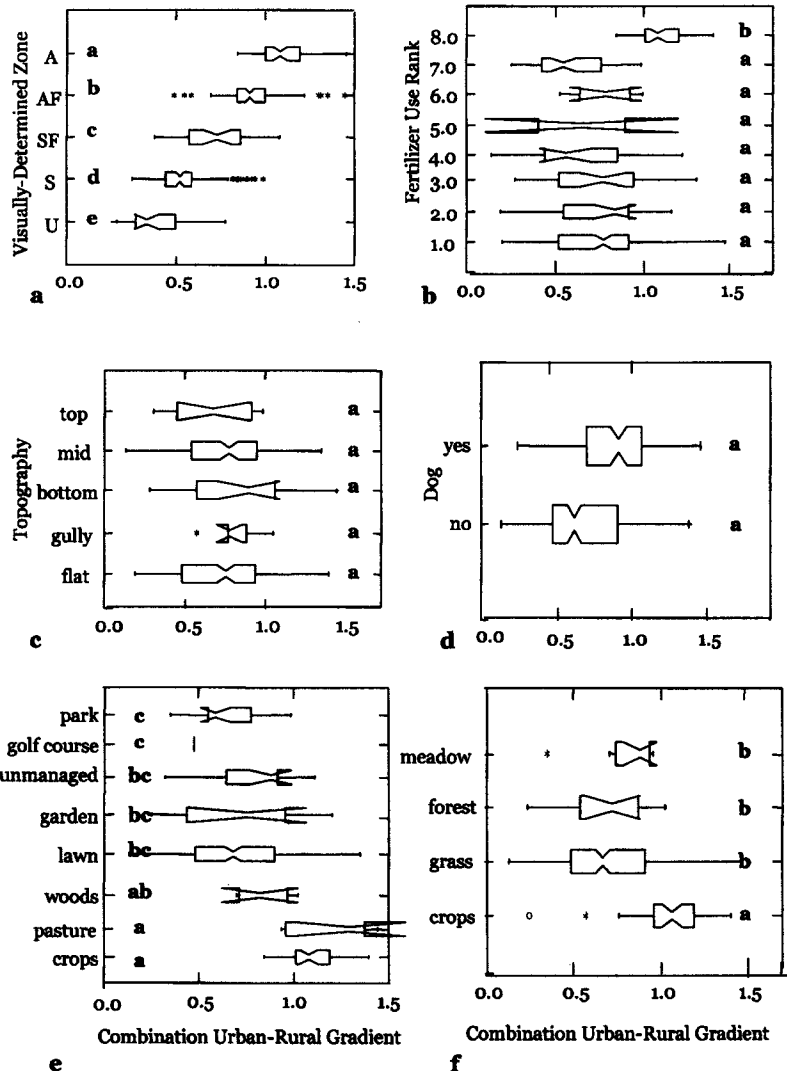
<sup>a</sup>Farms are excluded from house age analysis.

visually determined zone and the mapped urban-rural gradient value (Figure 5a). Slope, percent cover, and topography are not expected to vary in a predictable way across the gradient, so it is not surprising that these factors showed little correlation with the urban-rural gradient (Figure 5c). However, land use and land cover

were expected to change predictably across the gradient. This was the case for crops and pasture, which were generally found only at the agricultural part of the gradient (Figure 5e). However, many of the land use and land cover types (e.g., lawn and grass) were distributed across the entire gradient. Despite expectations, fertilizer use did not appear to vary in any predictable way across the urban-rural gradient (Figure 5b)

Finally, extractable soil P was not closely correlated to many measures of the urban-rural gradient. There were significant nonlinear relationships between Bray-1 P concentration and each of the gradients, but these relationships explained only 2.6%–3.3% of the variation in P concentrations (Figure 6). This relationship was consistent across each of the urban-rural gradients defined in this paper. In contrast to the fairly signifi-

**Figure 5.** Whisker plots of several categorical P predictor variables and the values of the combination urban–rural gradient. Lower urban–rural gradient values (unitless) indicate more urban sites, and higher values indicate more rural sites. (a) Visually perceived zone versus the combination urban–rural gradient. The visually perceived zone is the zone visually determined by the researcher during sampling based on a predetermined set of visual cues. U = urban; S = suburban; SF = suburban fringe; AF = agricultural fringe; and A = agricultural. (b) Fertilizer use rank versus the combination urban–rural gradient. rank 1, no fertilizer ever; rank 2, property is almost never fertilized; rank 3, fertilized by owner once per year; rank 4, fertilized by owner twice per year; rank 5, fertilized by owner three times per year; rank 6, fertilized by owner four times per year; rank 7, professionally fertilized; rank 8, agricultural fertilizers applied. (c) Topography (local to the sample) versus the combination urban–rural gradient (d) Presence or absence of a dog living on the property versus the combination urban–rural gradient. Yes means a dog resides on the property. No means no dog resides on the property. (e) Land use versus the combination urban–rural gradient (f) Land cover versus the combination urban–rural gradient



cant differences among maps, there was no real difference in the analysis among the gradients. A general linear model captured approximately 37% of the variance in the data using the urban–rural gradient, topography, land use, land cover, manure use, and soil type as predictors (Table 3).

## Discussion

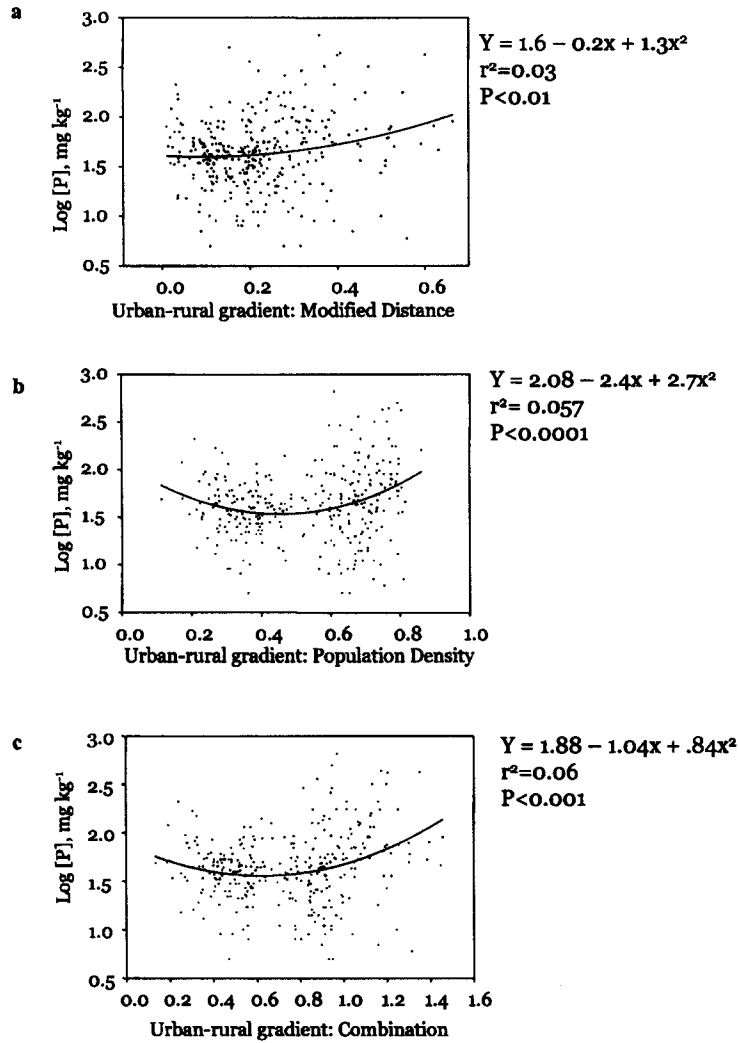
Extractable soil P concentrations vary substantially across Dane County soils. Approximately 37% of this variability can be explained by a combination of the indicators that I measured. Despite the application of several plausible definitions of the urban–rural gradient, the gradient is only weakly correlated with P concentrations and is only a minor contributor to multiple

regressions. There are statistically significant correlations between Bray-1 P concentrations and the urban–rural gradients, but the explanatory power of this relationship is weak.

The weak relationship between extractable P concentrations and the urban–rural gradient is unlikely to be an artifact of the data for several reasons: P variability was high, the sample size was large, and the sample design was carefully stratified and randomized. In fact, many statistically significant relationships exist in the data. However, these explain only a small amount of the variance and suggest that variability in P is large and unexplained by any of the covariates.

There are two types of factors that might preclude accurate predictions of extractable soil P using urban–





**Figure 6.** Data and best fit for the three urban-rural gradients versus log Bray-1 P. (a) Modified distance gradient versus log P. (b) Population density urban-rural gradient versus log P. (c) Combination urban-rural gradient versus log P.

**Table 3.** Results of the general linear model, produced by the backwards step procedure, for explaining extractable soil P concentrations in Dane County

Source	df	MS	F
Land use	7	0.432	4.56**
Topography	4	0.404	4.26**
Manure use	2	0.307	3.24*
Combination gradient	1	0.213	2.25
Soil series	28	0.192	2.03**
Land cover	3	0.097	1.02

\*For the model overall: R<sup>2</sup> = 0.369; F = 3.43; Pr < F is 0.0001. \*P < 0.05, \*\*P < 0.01.

rural gradients in Dane County, Wisconsin. One set of factors includes those that are particular to P as a response variable, but might be found across many urban-rural gradient studies. Another set includes fea-

tures of this urban-rural gradient that are different from other gradients.

Differences between other urban-rural gradients and this one can be used to investigate the applicability of urban-rural gradients as predictors in cities with different development patterns and as predictors across multiple land uses. Most applications of urban-rural gradients have involved very large cities and have ranged over hundreds of kilometers through an intense shift in land use from an extremely urban, high-use landscape to an extremely rural, low-use landscape. Many have also controlled for land use by sampling in only one particular land use of interest. In Dane County, the situation is different. Here, I was able to test the ability of an urban-rural gradient that traverses from one type of intense land use (urban) to another (agricultural) to predict extractable soil P. Urban-rural gradients have in the past often been defined along a

transect and involve sampling in one type of land use only, usually the most natural or least intensively used (e.g., McDonnell and others 1997, Pouyat and others 1997, Carreiro and others 1999, Medley and others 1995). For example, the New York to Connecticut (USA) belt transect studies were conducted in forested patches along a land use gradient (e.g., Medley and others 1995, Pouyat and McDonnell 1991, Pouyat and others 1997). I examined extractable soil P across multiple land uses using a multidirectional gradient because the goal of this study was to define a useful predictor of P concentrations across multiple land uses and across the entire county. While it is also possible that an urban–rural gradient exists in Dane County, but I failed to define it, this is unlikely because of the large number of factors I sampled and the generally low correlations of all of these factors with Bray-1 P.

Factors that increase the difficulty of predicting extractable soil P concentrations include the high variability of soil P and legacy effects of past land use and management that are not captured by the urban–rural gradient or the house age predictors (Baxter and others 2002). For example, two study sites might appear to be similar in all factors including house age, yet differ in some unmeasurable historical land use. While both might have been agricultural sites 40 years ago, one site might have been a high P input barnyard and another a less fertilized cornfield. This difference could lead to measurable differences in soil P concentrations for a reason that would be undetectable by this study. High inherent variability in soil may be due to geological and pedological factors that are not fully explained by soil type. Additionally, Bray-1 P may not have responded to urban–rural gradient factors at the appropriate time scale to be captured by the experimental design.

Scientists and managers are interested in predicting soil P storage as an indicator of P runoff potential. P runoff is a primary cause of eutrophication, and the pattern of P accumulation is likely to have an impact on the timing and amount of P runoff (Heckrath and others 1995). If predicting soil P accumulation was possible without extensive soil measurements, managers could easily target P hot spots of high runoff potential. Extractable P, such as that measured by the Bray-1 technique, has been shown to be related to P concentrations in dissolved runoff, but it may not capture particulate P runoff. However, the correlation of Bray-1 P with total P in Dane County (Figure 3) indicates that our measurements of P may have been able to capture relative concentrations of both total and extractable P in Dane County, thus providing a decent measure of overall runoff potential.

Even though the urban–rural gradient was not a useful predictor of P in this watershed, it nonetheless functions as a useful tool for organizing complex land use/land covariates (McDonnell and others 1997). Findings of urban–rural gradient studies have greatly increased our understanding of urban ecosystems. In one series of studies along a belt transect from urban Bronx County, New York, to rural Litchfield County, Connecticut, USA, human population density, traffic volume, and percent urbanized land decreased while mean forest patch size and percent forested land increased (Medley and others 1995). Heavy metal concentrations (such as lead, copper, and nickel) in soil decreased with distance from the urban center, and urban forest soils were more hydrophobic than rural ones (Pouyat and McDonnell 1991, Pouyat and others 1994). Maple leaf litter decomposition rates were higher in rural forest soils (Pouyat and others 1997), potential N mineralization and nitrification were higher in urban forests (Zhu and Carreiro 1999), and rural oak leaf litter quality, measured as ability to support microbial biomass, was higher than that of oak leaves from urban sites (Carreiro and others 1999).

Other studies have shown correlations between an urban–rural gradient and patterns of fish spawning (Limburg and Schmidt 1990), butterfly diversity (Blair and Launer 1997), breeding bird species composition (Natuhara and Imai 1996), and animal foraging behavior (Bowers and Breland 1996). A study of landscape pattern along an urban–rural gradient in the Phoenix, Arizona, USA, area revealed that mean patch size changed significantly along the urban–rural gradient as defined for this area (Luck and Wu 2002).

Urban ecology is still in its infancy. As the science matures, we expect to gain a clearer picture of which ecosystem variables change systematically along urban–rural gradients and which do not. My study shows that extractable soil P is not well predicted by urban–rural gradients in an urbanizing agricultural area and suggests that geological, pedological, and human legacy effects may preclude any simple relationship between the urban–rural gradient and extractable soil P. A synthetic understanding of what urban–rural gradients can predict and what they cannot will be a significant milestone in the development of urban ecology.

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