Society and Natural Resources, 19:153–173
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ISSN: 0894-1920 print/1521-0723 online
DOI: 10.1080/08941920500394816

Disproportionality as a Framework for Linking Social and Biophysical Systems

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Interdisciplinary research is capable of investigating questions that no single or independent collection of disciplines can address. This interdisciplinary approach was used to investigate why nonpoint source pollution to a lake had not changed even though the often cited social drivers of this situation had changed significantly. The concept of disproportionality was adapted to examine social and biophysical interactions at different spatial and temporal scales to address this situation. Rather than using social and biophysical variable as contextual or additive relative to each other, we examined their interactive or multiplicative effects at coarse and fine spatial and temporal scales. Limited occurrence of inappropriate behaviors in vulnerable biophysical settings resulted in disproportionate environmental impacts. The concept of disproportionality implies that the environmental meaning placed on any social behavior requires accounting for where and when it occurs in a biophysical setting, and that a few outliers can determine system performance and outcomes.

Keywords agriculture, cross-scale, development, disproportionality, eutrophication, interdisciplinary, nonpoint source pollution, space and time

Received 13 April 2004; accepted 8 June 2005.

The publication of this article was supported by Water and Watersheds grant R-82801001 from the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) program and grant 2001–04610 from the USDA-CSREES-IFAFS program. We also received partial support from the NSF–Long Term Ecological Research, Northern Temperate Lakes program. Heartfelt thanks to the anonymous reviewers who provided thoughtful suggestions to an earlier version of this article.

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Developing partnerships that foster research integration between the social and ecological sciences can be challenging. These partnerships, if they do emerge, are extremely fulfilling as they enable scientists to extend their own expertise by bringing different perspectives to bear on problems beyond the scope of any single discipline. The traditional research structure, however, has been slow to recognize the unique value that these partnerships offer in the formulation, investigation, and publication stages of scientific inquiry. This long-established structure has even been described as a hindrance to the creative intellectual context that emerges from true interdisciplinary collaborations (Nissani 1997). In this article, we describe some of the insights that we have gained by participating in an interdisciplinary research partnership involving the social and ecological sciences. Our specific objective is to introduce an adaptation of the *disproportionality concept*. We argue that this concept not only provides a framework for strengthening partnerships between social and biophysical scientists, but also offers an alternate perspective for evaluating resource management effectiveness.

Long-Term Ecological Research: An Interdisciplinary Endeavor

Inputs of phosphorus (hereafter referred to as P) to Lake Mendota, the largest of the southern lakes studied by the North Temperate Lakes Long Term Ecological Program (NTL-LTER), have long been of interest to limnologists seeking to understand the process and pace of lake eutrophication, a major problem in freshwater lakes characterized by excessive cyanobacteria (blue-green algae) growth, dissolved oxygen depletion, and aquatic biodiversity loss (Schindler 1977; Carpenter et al. 1998; Smith 1998). Social scientists became involved in the NTL-LTER in 1995 when the research program was augmented to include land use and watershed management impacts on P loads[1] to the lake.

One of the first questions confronting the new NTL-LTER partnership was, "How could land use and management have changed significantly in some regions of the Lake Mendota watershed over the prior two decades without prompting a decrease in P loads to the lake?" This question is a familiar one in the field of resource management, and often arises when conservation or watershed protection programs are underperforming. In an overview of the revised Wisconsin Nonpoint Source Water Pollution Abatement Program, for example, Wolf (1995) evaluated the effectiveness of this program at improving aquatic habitats by reducing sediment, nutrient, and pathogen loads. The author reported that landowner participation, which was voluntary, was generally too low in terms of sign-up to have resulted in significant water-quality improvements. The NTL-LTER partnership was also asking this question relative to one of Lake Mendota's tributaries, the Pheasant Branch Creek, with a drainage area of 43.4 km^2. The total P load from this watershed had not changed dramatically for a two-decade period of extensive monitoring between 1976 and 1994 (Lathrop 1998). This observation was surprising because land use and management in this watershed had changed significantly during this period, and these changes should be expected to reduce P delivery to the lake. For example, major advances had occurred in agricultural nutrient management technology that were adopted by farmers, much land had been converted from agricultural to urban uses, and significant conservation expenditures had been allocated to the agricultural regions of this watershed. Therefore, it was surprising to the partnership that P loads had not changed significantly during this 20-year period.

The Concept of Disproportionality

Social scientists have typically addressed the question of conservation program effectiveness by focusing on aggregate patterns of land user behavior, such as examining the extent of adoption of remedial/preventive practices, correlating stakeholder environmental attitudes with demographic characteristics, or assessing institutional mechanisms associated with land markets and resource management programs. In this analysis, however, we employed a different approach. Rather than treating the social and the biophysical variables as contextual or additive relative to each other, we examined their interaction at different spatial and temporal scales. Our rationale for this approach was based on a preliminary investigation of the research setting where we found extreme outliers within both the social and biophysical settings. Outliers in environmental research are often either addressed through statistical manipulation or removed from subsequent analyses, but our observation of these outliers emphasized their potential importance in understanding social and biophysical system dynamics across time and space. Consequently, we turned to the concept of disproportionality in an effort to account for the impact of these outliers.

Disproportionality has been examined in three broad realms of social science. First, research on environmental justice has investigated how negative environmental conditions (e.g., air quality, land use, water quality) disproportionally impact certain groups, classes, or minorities (United Church of Christ for Racial Justice 1987; Mohai and Bryant 1992; Bullard 1996; Downey 1998). This research generally concludes that the distribution of negative environmental impacts on human populations is not random, but is instead structured by social processes. An ongoing subject of debate in the environmental justice literature has been the spatial scale at which relations between measures of degradation and social organization should be examined (Taquino et al. 2002; Bowen and Haynes 2000). Instead of selecting existing political boundaries (e.g., Census tracts, ZIP codes, counties), it appears more appropriate to select scales of social organization congruent with the scales of the biophysical degradation processes (e.g., airsheds, groundwatersheds).

Second, the concept of disproportionality is found in social science research that investigates patterns of social sanctions and interaction. This is an extensive area of research that examines how certain minority groups may be disproportionately subjected to state sanctions (e.g., police stops or searches) or other forms of social discrimination such as racism or sexism (Holden and Smock 1991; Serwatka et al. 1995; Washington 1996). A subset of this research theme examines the political and social actions taken where consequences are not proportionate to the composition of the participating groups (see Hill and Leighley 1994). A minor example of this subset is Marx's Law of Disproportionality, which states that fluctuations and periodic crises in economic markets are caused by disproportionate rates of production and consumption. Marx argued that economic equilibrium is a myth, and in fact, the periodicity may become so severe as to instigate rebellion from the consumers. A more recent example by Firebaugh (1999) examines whether income inequality among nations is converging or diverging relative to past disproportionate distributions of wealth. The spatial units of analysis are again demarcated by social organizations. The general research question is whether wealth or engagement is proportionate to the size of these social organizations.

The third general area of disproportionality research in the social sciences examines the difference in the environmental impact associated with different forms of

social groups. This area was pioneered by ecological researchers and is best represented by the popular notion of the "ecological footprint," which represents the total goods and services used by particular social groups (Wackernagel and Rees 1996). This concept has been applied to nations, industries, and even families. Disproportionality is cited in this literature when examining the relative ecological footprints of different groups. York et al. (2003) used the ecological footprint approach to test the relative efficacy of theories of human ecology, modernization, and political economy in positing the relationship between industrial development and environmental impact. Generally, the ecological footprint research is used to point out disproportionate impacts between groups on the use (or misuse) of environmental goods and services (Vaillancourt 1999). A number of methodological issues emerge (Ferguson 2002) in assessing direct and indirect impact measures, but in general, the scale of the ecological footprint is equated with the average consumptive processes of the social groups being examined.

The primary focus of all three of the disproportionality research traditions is based on the examination of between-group variation, where the spatial scale is predetermined by the boundaries of the social groups being examined. That is, the focus is on statistical differences in measures between groups in regard to exposure to environmental pollution, imposition of sanctions, changes in wealth, or impact on ecosystems. The central research question in all of these approaches is whether some impact being caused or experienced by a particular group is more or less extreme than the causes or experiences of different groups. The parameter representing the group, whatever that may be, is the average within a social boundary that is used to represent the group. Disproportionality is cited when the average impact of a group is significantly greater than the average impact of other groups. In this article, we suggest that the concept of disproportionality can also be applied to measures of *within*-group variation. This form of disproportionality is especially salient when examining the interaction between social and biophysical processes.

It is critical to emphasize that this adapted form of disproportionality can only be discerned by using an interdisciplinary approach that measures the interactive or multiplicative effects between social and biophysical systems. For example, an inappropriate land-management practice may be environmentally benign in a well-buffered biophysical setting, whereas an appropriate practice may be very detrimental in a particularly vulnerable biophysical setting. Research that correlates overall group averages of behavior (e.g., adoption rates of remedial techniques) with aggregated measures of environmental processes (e.g., pollutant loading from a watershed, habitat degradation in an ecoregion) will miss this form of disproportionality. We view this form of disproportionality as the degree of asymmetry between a specific social behavior, or a set of behaviors, and the resiliency or buffering capacity of the biophysical setting (i.e., space and time) where these actions occur.

Limpert et al. (2001) elucidated this concept concisely in a seminal paper juxtaposing the "normal world" and the "log-normal world." These authors argue that the latter is more often the case, citing many of the fundamental biological, physical, and social processes that are characterized by log-normal probability distributions. Probability distributions are helpful for understanding our suggested adaptation of the concept of disproportionality for two reasons. First, when social behaviors relative to the environment have been measured, the distributions of these behaviors were characterized by positively skewed normal or even log-normal probability distributions. Nowak et al. (1998) and Shepard (2000), for example, observed that the

distribution of fertilizer application rates by several thousand farmers in Wisconsin contained a small fraction of outliers applying nutrients many times greater than recommended rates and the mean of the distribution. The U.S. Environmental Protection Agency (U.S. EPA) toxic release data also illustrates that emissions of pollutants from industry exhibit log-normality (Freudenburg and Gramling 1994). Figure 1a illustrates this pattern of probability in regards to environmental behavior. Second, assessments of the vulnerability of biophysical settings to human disturbance are also characterized by skewed normal or log-normal probability distributions, as illustrated in Figure 1b. For example, the majority of erosion from U.S. cropland comes from only a small proportion of total cropland (USDA-NRCS 2003). Research on P movement from watersheds indicates that in many cases, pollution can be driven by the processes taking place in a very limited number of critical source areas (Gburek and Sharpley 1998). As illustrated in Figure 1c, disproportionality emerges as the multiplicative effect of these two distributions; a small

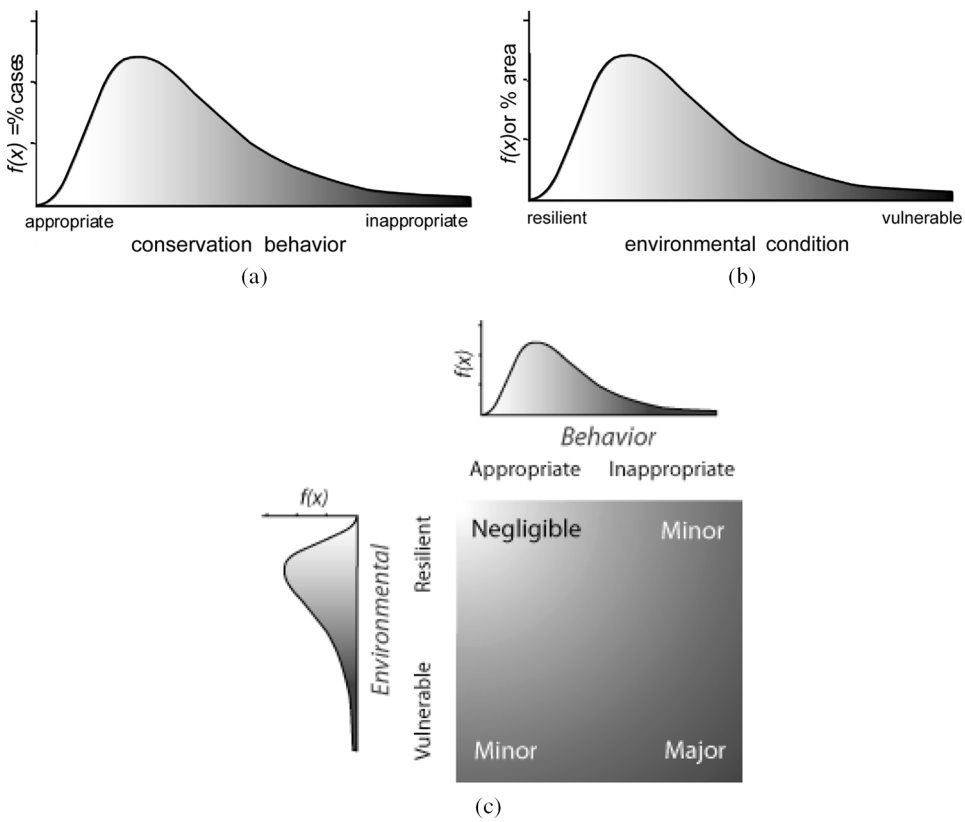


Figure 1. (a) Typical conservation behavior adapted from Nowak et al. (1998) and Shepard (2000) indicating a skewed normal or log-normal probability distribution; (b) Typical environmental condition indicating a skewed normal or log-normal probability distribution of the probability of environmental risk; (c) Multiplicative effect of probability distributions of conservation behavior and environmental setting. A small proportion of inappropriate social behaviors within a particularly vulnerable setting may have a disproportionately large impact on overall environmental quality of an ecological system.

proportion of inappropriate social behaviors within a particularly vulnerable setting can have a disproportionately large impact on overall environmental functioning of an ecological system.

Our conception of disproportionality emphasizes that human contributions to environmental degradation are not normally or randomly distributed, but arrayed in a way that may be strongly skewed and determined by the specific biophysical setting where it takes place. This view of disproportionality is a derivative of Robinson's (1950) ecological fallacy in that the environmental performance of a unit of social organization does not imply that all individuals within that organization perform in a similar fashion. Because logging, mining, agriculture, or suburban development degrades the environment, for instance, this does not mean that all loggers, miners, farmers, or developers are equal contributors to degradation. The classic scientific caveat, "It depends," conditions the impact of behavior based on the setting of that behavior. Furthermore, the log-normal world suggested by Limpert et al. (2001) implies that a very small minority within a social group may cause significantly greater environmental degradation, and possibly more than the combined impact of the remaining group. This disproportionate outcome occurs, not because the behavior of the minority is especially egregious or deviant, but because their actions are inappropriate behaviors taking place in biophysically vulnerable settings or times.

Employing this concept of disproportionality suggests that environmental sociologists need to account for both the distribution of behaviors within social organizational boundaries and, equally important, the distribution of the resiliency of the biophysical settings of those behaviors. Acknowledging that disproportionality may drive the improvements or degradation in an ecological system requires social scientists to explicitly account for *within*-group variation of social actors. Depending on the biophysical setting, only a few cases may have a disproportionate impact on the overall ecological system being studied. The potential for this form of disproportionality implies that the environmental meaning placed on a social behavior requires accounting for where and when it occurs in a biophysical setting. We emphasize that the social interpretation placed on any behavior by environmental social scientists, and any subsequent analysis of the ecological impacts of this behavioral pattern, must take into account where and when the behaviors occur in an ecological setting (Abbott 1999). The interaction between the characteristics of the behavior and the biophysical setting where the behavior occurs should determine the meaning placed on that behavior. For example, the all-too-common term of "bad actor" is only partially correct; both the "acting" and the "stage" for that action need to be used in forming such ill-advised value judgments. In our examination of the Pheasant Branch watershed, we found that the concept of disproportionality offered an approach to addressing the question of why significant changes in the social system did not induce parallel changes in the biophysical system.

The Pheasant Branch Creek Watershed

Lake Mendota is the largest of the lakes surrounding Madison, WI. A rich set of long-term data on various limnological features of the lake is available from the University of Wisconsin Center for Limnology (UW-CFL), including the relationship between settlement patterns and the resulting accelerated eutrophication of the lake (http://lter.limnology.wisc.edu). It is estimated that human activities

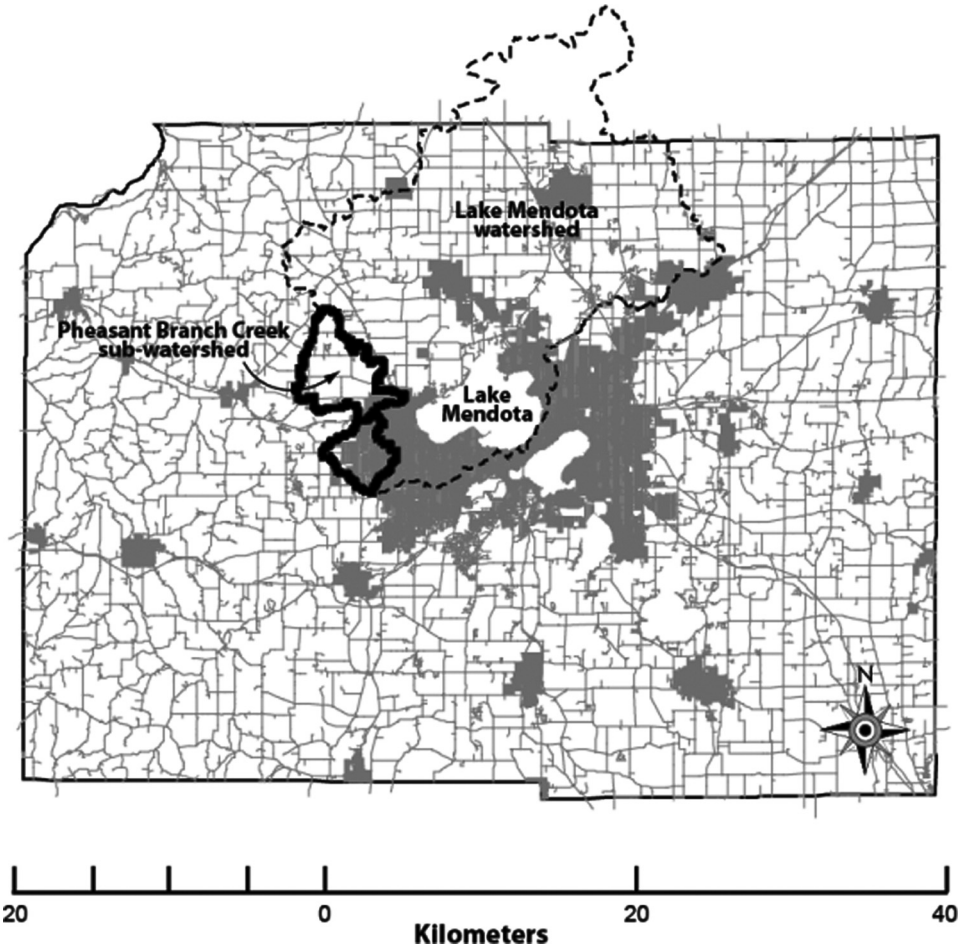


Figure 2. Pheasant Branch Creek subwatershed situated within the NTL-LTER study watershed (Lake Mendota) in Dane County, WI.

accelerated lake eutrophication in the mid-1800s (Reed-Anderson et al. 2000), and anthropogenic sources of pollution continue to dominate the ecological status of the lake (Carpenter and Cottingham 1997). The subwatersheds of Lake Mendota studied by the NTL- LTER represent a continuum of land uses, from fully urbanized to those still dominated by agricultural systems.

The Pheasant Branch Creek is fed by a subwatershed located on the western edge of the greater Madison urbanizing area (Figure 2). The U.S. Geological Service (USGS) and the UW-CFL have monitored runoff and sediment delivery rates from this subwatershed since 1978.

Social Change and Disproportionality in the Pheasant Branch

Our adaptation of the concept of disproportionality suggests that it is necessary to examine salient social dynamics relative to their biophysical settings. Examination of this sort needs to be cognizant of the importance of interactions between social

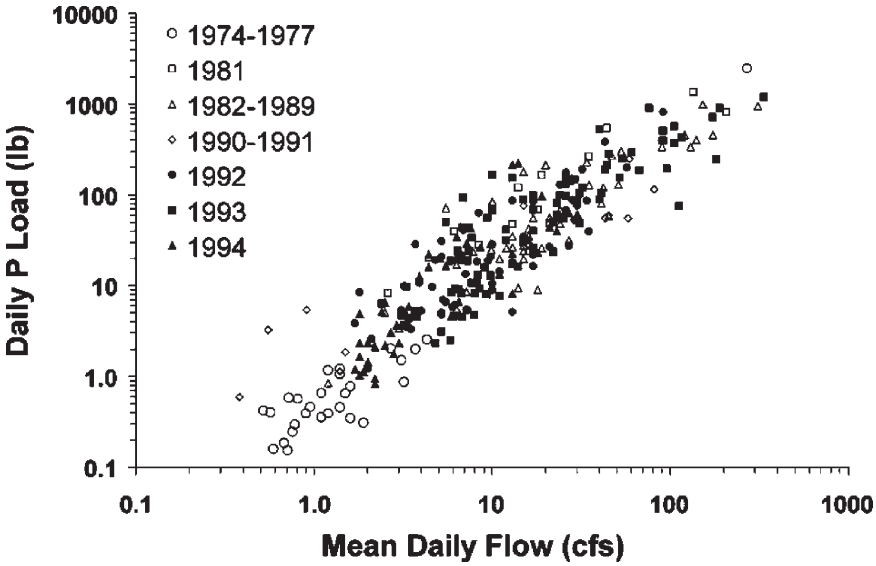


Figure 3. Daily P loadings (lb) versus mean daily flows (cubic feet per second, cfs) for flow in the Pheasant Branch Creek subwatershed (Lathrop 1998).

and ecological processes at multiple spatial and temporal scales (Carpenter and Cottingham 1997; Carpenter and Leavitt 1991; Gunderson et al. 1995; Levin 1992; Ludwig et al. 2000). Ecologists note that processes occurring at one spatial scale can impede or facilitate processes occurring at coarser or finer spatial scales (Allen and Hoekstra 1992). This confounding multiscale interaction and response also occurs in the temporal realm (Campbell et al. 2001), when infrequent but large disturbances may structure an ecosystem for centuries, or the effects of human land use persist in ecosystems long after the activity has ceased (Carpenter and Turner 2001). This suggests one must consider *slow variables* and *fast variables* at both the coarse and fine spatial scales in which they operate (Carpenter et al. 1999; Levin 1992).

As exemplified in Figure 3, which indicated that P loading had not changed significantly from 1974 to 1994, the interdisciplinary context of NTL-LTER research in the Pheasant Branch had social and biophysical scientists asking themselves, "What might explain how the social context could change so significantly in the Pheasant Branch without a comparable change in the ecological impact?"

Coarse-Scale Disproportionality

Agricultural enterprises encompassed by the Pheasant Branch Creek subwatershed have changed significantly since the turn of the 20th century. Agricultural operations in the Pheasant Branch Creek subwatershed have shifted from subsistence farms using horse and single-bottom plows across small, spatially concentrated fields, to large livestock farms employing the latest biotechnological and electronic innovations on large, spatially disparate fields. Consistent with national trends, the transition has been toward fewer, larger farms that increasingly adopt productivity-enhancing technology in an attempt to remain competitive in markets that are increasing in geographic scope. Now, at the beginning of the 21st century, fewer

multigenerational farms are competing in global markets using the latest technologies consistent with the role of technological revolution in the history of American agriculture (Cochrane 1993).

Farms in this subwatershed, like farms everywhere, historically valued animal manures as an on-farm resource. Manure was used as a soil nutrient to increase crop productivity, thus allowing the farmer to enhance soil quality while being a good steward of the land. At the beginning of the 20th century, Reverend Evast preached to his Wisconsin congregation that "where there is manure, there is Christ" (Zeitlin 1977). This remark epitomizes the importance placed on the husbandry of animal manures in the first half of the 20th century. However, by the late 1940 s, attitudes toward manure had changed dramatically. This was due to the widespread promotion and availability of commercial fertilizers following World War II coupled with the occurrence of the "Green Revolution." Animal manures were being redefined from a valuable on-farm resource to simply being a "waste." Land grant universities, agribusinesses, and farm consultants began actively promoting the benefits of commercial fertilizers while implicitly encouraging farmers to dispose of animal manures without effectively crediting nutrient values (Dittrich 1993; Nowak et al. 1998). Consequently, at least two generations of farmers in the Pheasant Branch Creek region were taught to land-apply manure by dumping or disposing of it in convenient locations consistent with the notion of manure being a waste (i.e., waste management). While manure management was being relegated to waste disposal, farmers were busily expanding their operations with more animals that further elevated overall P level of the soils within the watershed.

The institutional processes that redefined manure from being a valuable, on-farm nutrient source to being a waste created a biophysical legacy in the form of massive soil P surpluses within the watershed soils. The important point is that these biophysical features (i.e., excessive soil P levels) were not distributed uniformly across the landscape in the Pheasant Branch subwatershed. Instead, the "hot spots" of soil P were spatially distributed in a pattern that coincided with or were proximate to former or current livestock operations. Watershed P budgets (Bennett et al. 1999) and P dynamics for the entire Lake Mendota system (Reed-Anderson et al. 2000), however, were based on average P levels across the entire watershed. While both studies showed an average buildup of P in agricultural soils across time, neither addressed the heterogeneous spatial patterns of soil P induced by human behaviors. These patterns of elevated soil P levels create what ecologists call a "slow variable" in that it would take tens of years for crop production to draw down these levels to more typical agronomic concentrations.

The 1960s represented the appearance of a new "fast variable" in this agricultural watershed as development began to accelerate in the Pheasant Branch Creek subwatershed (Figure 4). Development involves construction processes that scarify the vegetative cover, greatly increasing the probability of excessive soil erosion. Development also increases the area covered by rooftops and streets that are impervious to infiltration. Before development, rainfall slowly infiltrated into agricultural soils and stream conditions were relatively stable. Unless the rainfall is infiltrated or detained in some way, the increased imperviousness can make for a more "flashy" hydrologic system, with higher peak flows and more runoff.

Development does not occur in a uniform "wave" from urban to rural areas, but often "leap-frogs" and creates a heterogeneous patchwork of urban and residential areas, intermixed with agricultural land uses (Figure 4). More importantly, locations

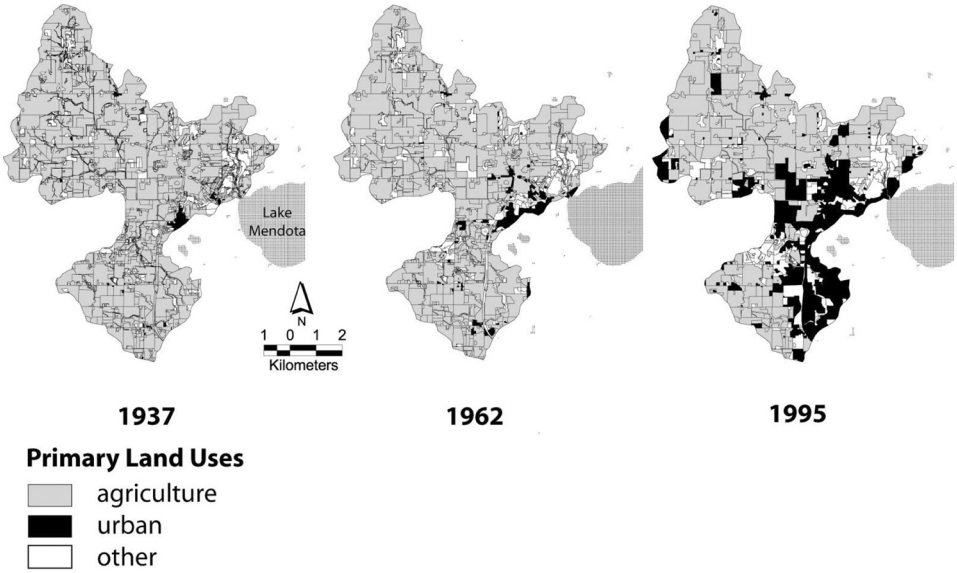


Figure 4. Changes in land use from 1937 to 1995 in the Pheasant Branch Creek region.

for development are not influenced by existing soil P levels, but are determined by market and other social processes. Regulations and the design of preventive practices associated with construction activities are also independent of soil P levels at the construction site. One set of standards and regulations applies to all development in the jurisdictional area, regardless of soil P levels. Consequently, the conditions for disproportionality to occur had been established in this watershed in that biophysical conditions were being treated independent of social processes. When development processes occur in a location with a biophysical legacy (i.e., P-enriched soils), the exposure of these P-enriched soils to storm events that may occur during the construction process can cause a short but intense pulse of P delivery. This short but intense pulse of P represents a disproportionate contribution to normal P dynamics at the watershed scale.

A study by Owens et al. (2000) found that a small (<5 acres) commercial development in this watershed eroded over 8 tons of sediment per acre during the 3 months of active construction. The annual average erosion rate, however, across the full year would be significantly less, due to the subsequent construction of impervious surfaces and grassy areas. Based on an annualized average, therefore, this short period of excessive erosion is not seen as a problem when the typical upper threshold for agricultural fields is 5 tons per acre across a full year. Therefore, although only a small fraction of land is being developed in any given year, and even though the soils at this development site are only exposed for a short period, if this small area occurs where there is a biophysical legacy, then it can make disproportionate contributions of P to the lake.

Shortly after social science became an integral aspect of NTL-LTER research, the Wisconsin Department of Natural Resources (WDNR) began developing a plan to reduce nonpoint pollution to Lake Mendota, which culminated in the *Nonpoint Source Control Plan for the Lake Mendota Priority Watershed Project* (WDNR 1997). This plan estimated that <2% of the land area of the watershed was in

transition from agricultural to developed land. However, this relatively minor area contributed ~23% of the total P mass delivered to Lake Mendota. Using data from 1998 (water year), Steuer and Hunt (2001) illustrated that a developing commercial/residential area comprising only 16.3% of total drainage area contributed 36.6% of total P load in stream flow from the Pheasant Branch (Table 1). None of the cited studies accounted for the soil P levels prior to construction activities.

This long-term and independent interaction of social and biophysical processes set the stage for disproportionality to occur. That is, land-use events (i.e., development) that meet all regulatory requirements (i.e., construction site erosion ordinances) but occur in a vulnerable location (i.e., P-enriched soils) and time (e.g., heavy rains) can flush large amounts of P-enriched sediment into the lake during a very short period. While the background levels of P delivery for the watershed may be decreasing due to changes in conservation behavior and land use, a coarse-scale disproportionality analysis would suggest that these infrequent, large pulses of P may have been responsible for maintaining consistent conditions at the historical, aggregate level depicted in Figure 3.

We argue that despite the aggregate improvements in manure management and conservation investments through federal, state, and local programs, disproportionate contributions to sediment and P loading from the Pheasant Branch Creek began to dominate the water-quality characterization of the subwatershed. The relation between investments in federal conservation programs and sediment delivery is presented in Figure 5, a and b. Federal conservation program data were only available for the portion of the study period, beginning near the inception of the WDNR Priority Watershed Project, and investments probably increased as a result of provisions in the 2002 Farm Bill. One would expect a negative relation between investment level and measures of degradation if these programs were effective, but there is little support for this hypothesis as illustrated in Figure 5, a and b. This is not surprising, since conservation programs are generally designed for the "average" rather than the exceptional, which have the potential to define overall environmental system performance.

In particular, the interaction of a slow variable (P buildup) with a fast variable (development) in a spatially independent fashion[2] creates the conditions for behaviors to have exceptional consequences. This occurs in two ways: (1) exposed P-enriched soils on construction sites that are exposed to storm events creating short but intense pulses of P; and (2) flashier hydrologic system releases of P that would not be transported under average hydrologic conditions. Relatively small land areas and hydrologic periods are now having the same impact as was occurring in the past, from the agricultural area of the watershed under the preconservation and the "manure as a waste" period. This is disproportionality in action. Behavior, land use, conservation policy, and technology all changed between 1976 and 1994, but the loadings to the aquatic system remained essentially unchanged. Looking for the disproportionality that emerges from the interaction of social and biophysical processes at coarse spatial and temporal scales may be one explanation for constant P loadings from 1976 to 1994.

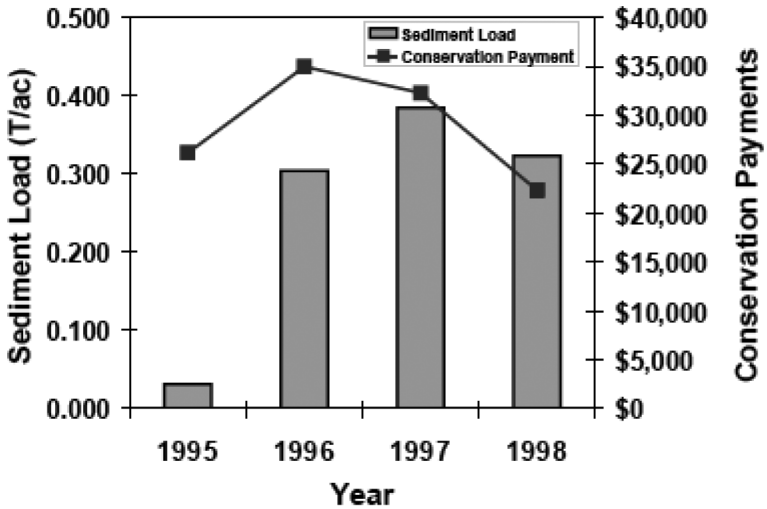
Fine-Scale Disproportionality

We also looked for evidence of disproportionality by moving from the coarse scale of the subwatershed over the long-term, to the finer scale of individual agricultural

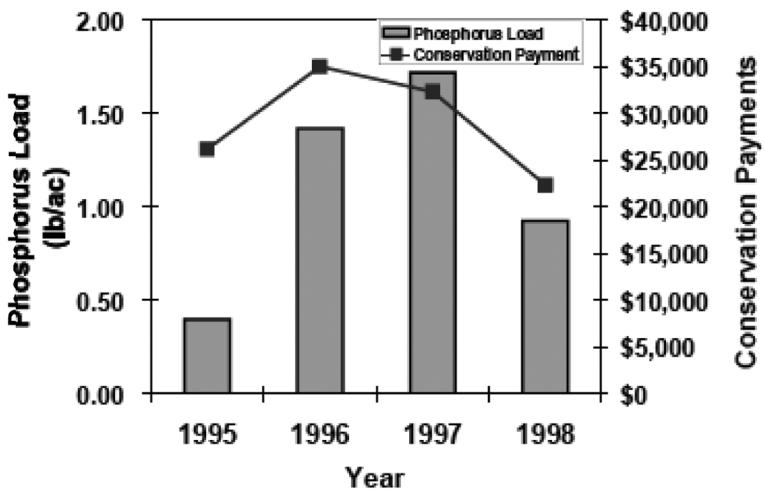
Table 1. Water volumes, sediment loads, and P loads in the Pheasant Branch Creek for water year 1998 (adapted from Steuer and Hunt 2001)

Description	Drainage area (mi^2)	Water volume (cfs-days)	Water volume by area (cfs-days/mi^2)	Suspended sediment (tons)	Sediment production by area (tons/mi^2)	Phosphorus (tons)	Phosphorus production by area (tons/mi^2)
Northern agricultural	9.6	570	59.38	300	31.25	3290	342.71
Southern agricultural	5.7	570	100.00	560	9.82	1450	254.39
Commercial/residential	3.0	710	236.67	1820	606.67	2610	870.00
Total area	18.3[a]	1850	101.09	2680	146.44	7350	401.64

[a] Historically, 1.22 mi^2 of the drainage area does not contribute to surface runoff.



(a)



(b)

Figure 5. (a) Sediment load (T/ac) versus conservation payments in the Pheasant Branch Creek subwatershed (1995–1998). Conservation payments were acquired from the Environmental Working Group. Sediment loads are available from USGS Water Resource Data; (b) Phosphorus load (lb/ac) versus conservation payments in the Pheasant Branch Creek subwatershed (1995–1998). Conservation payments were acquired from the Environmental Working Group. Phosphorus loads are available from USGS Water Resource Data.

fields within a shorter time period. In order to test whether disproportionality could be occurring at these fine scales, we first looked for the following three factors, which are precursors to P migration from agricultural fields:

- Soil P levels (milligrams of P per kilogram of soil).
- Soil erosion potential (tons of soil loss per acre), based on the Universal Soil Loss Equation by Wischmeier and Smith (1978).
- Phosphorus index rating, based on Lemunyon and Gilbert (1993).

A critical social process influencing environmental outcomes is the management decisions that govern the distribution of animal manures across the agricultural landscape. This social process varies significantly in both space and time in terms of where and when manure is distributed. The "where" is governed by a complex set of informal rules related to land availability, crop rotations, current soil nutrient levels, and labor routines. The "when" can vary from a day-to-day basis to semi annual events with significant variance due to climatic events, and farm firm processes. The outcome of this social process also establishes a "record" in the form of measurable nutrient levels in the soils. Researchers can take soil samples across an agricultural landscape to get some idea of where manure was and is being distributed. This is especially the case for P which tends to become absorbed in the surface of the soil.

The results from the soil P tests from the nine active commercial farms that participated in our study are represented in Figure 6a. Nine of the 10 commercial farms in the watershed study area allowed researchers on their fields to obtain soil samples based on a 1-ha sampling grid (Cabot and Nowak 2005). In total, 3410 environmental soil samples (i.e., 5-cm samples using Bray 1 protocols) were taken across the 217 fields (1267 ha) managed by these farms in the watershed. The majority of the soil test results are in the high or excessively high range for P values, with a clear subset of outliers that have values up to 900% above the sample mean. Many of these higher soil test values are due to the legacy effects of treating manure as a waste over several generations of farm families. Even though soil test results are characterized by a log-normal distribution consistent with the insights of Limpert et al. (2001), this by itself does not represent disproportionality. Disproportionality occurs when we have inappropriate social actions occurring in vulnerable biophysical settings. Therefore, it is necessary to also look at the biophysical context before placing an interpretation on the landscape record of these manure management behaviors.

We examined two variables that help to categorize the biophysical setting relative to their vulnerability to these social actions: soil erosion potential and the phosphorous index. Potential soil erosion can be estimated using the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978). We calculated the potential soil erosion values for the 217 fields in the study area. Soil loss is correlated with P delivery because erosion processes are a critical mechanism driving the migration of P-enriched soils off fields into riparian areas. The USLE is a simple multiplicative index that combines the effects of rainfall, tillage, cropping, soil erodibility, topography, and conservation practices. Figure 6b illustrates that the majority of fields for which the USLE was calculated show erosion rates less than the acceptable tolerance value (T-value) of 5 tons of soil eroded per acre. There is, however, a highly skewed distribution with a few significant outliers. The estimates of soil erosion illustrated in Figure 6b combine management and some biophysical characteristics. However, if we are interested in nonpoint source P pollution, then we also need to explicitly account for the P levels in these soils based on the soil sampling discussed earlier and current manure application rates.

We accounted for P levels in the soils by calculating the phosphorous index (PI) for each field. The PI was developed by Lemunyon and Gilbert (1993) and accounts for soil P level, erosion, and manure application rates. Manure application rates (in kilograms P per hectare) for each field were estimated from on-farm interviews with the nine producers managing animal operations in the Pheasant Branch. The resulting index is an ordinal scale that weights the vulnerability or risk incurred by the

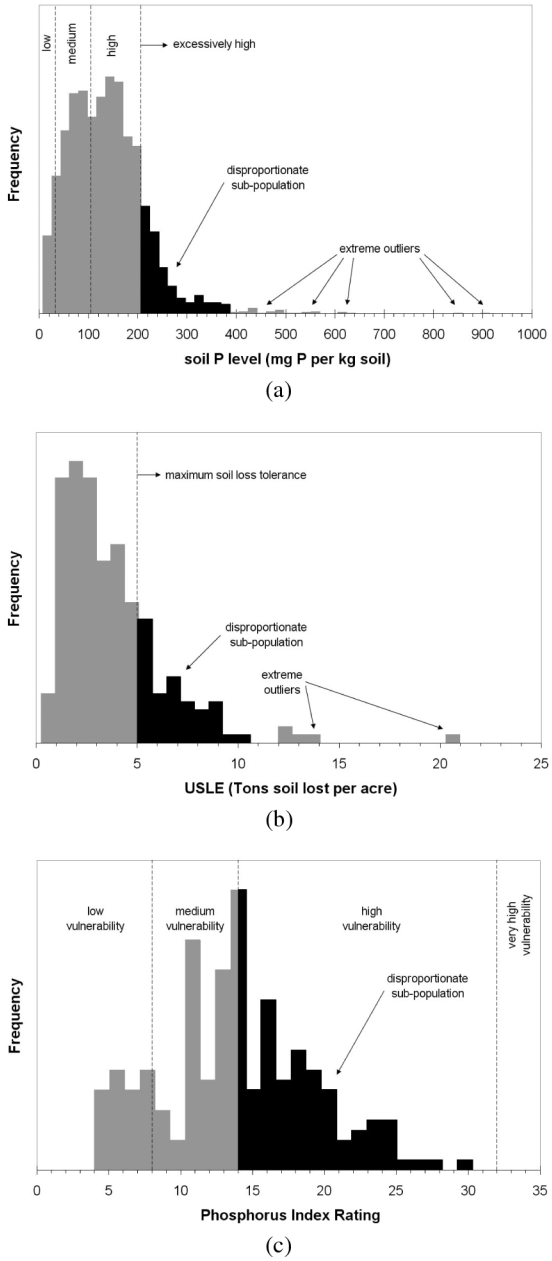


Figure 6. (a) Soil test P levels from 3410 samples taken across 19 farms in the Pheasant Branch Creek subwatershed (2000); (b) Universal Soil Loss Equation ratings for 19 farms in the Pheasant Branch Creek subwatershed (2000); (c) Phosphorus index rating for 19 farms in the Pheasant Branch Creek subwatershed (2000).

estimates of these parameters for each field. Low soil P levels (10–30 mg P/kg soil) are weighted with a "1," for instance, whereas high soil P levels (> 200 mg P per kg soil) are weighted with an "8." Similar weighting schemes are used for soil erosion,

chemical and organic P application rates, and rainfall runoff potential. The resulting PI ratings, another simple multiplicative index, for a subpopulation of fields in the Pheasant Branch are shown in Figure 6c.

Figure 6c illustrates that approximately half of the fields have a low or a medium vulnerability rating whereas the other half have high vulnerability ratings. What is not illustrated in Figure 6c is the interaction that occurs between the biophysical setting and social processes. For instance, some of the fields with a high biophysical potential for erosion are managed exceptionally, with all conservation practices in place and no manure application, which allows for the maintenance of moderate P levels. From a purely biophysical perspective, these fields would be viewed as vulnerable and targeted for remedial action, but the human dimension has nullified this vulnerability through behaviors that are appropriate to that specific setting. Conversely, some of the fields in Figure 6c have a fairly low biophysical vulnerability assessment, but behaviors inappropriate for this type of setting may have pushed them into the high risk category. Disproportionality occurs as an outcome of the interaction of the biophysical and social dimensions that are salient to the environmental processes being investigated. This suggests that P transport from a relatively small proportion of all fields is maintaining the long-term P loading as observed at the outflow of this watershed.

Applying the concept of disproportionality also provides some insights as to what is likely to happen in this watershed in the future. As development continues to expand and constrain farmer manure distribution decisions even further by taking more agriculture land out of production, the P levels will continue to build up on these remaining agricultural lands. This implies that in the future it will take smaller and smaller proportions of land being developed annually in order to maintain the current state of P vulnerability. As Allen and Hoekstra (1992, 247) note, "Things which are inert at a small scale can often be expected to be critically reactive at a large scale." This P buildup at the field scale, though it may not be on highly vulnerable agricultural land, increases the probability for disproportionate degradation in the future when development does occur. This is a simple example of how cross-scale interactions between social and biophysical factors have primed the Pheasant Branch to continue disproportionate P loadings into the future.

The Implications of Disproportionality for Interdisciplinary Collaboration

We are suggesting that indicators of environmental degradation in this situation (P loadings to Lake Mendota) failed to decrease during the 1976–1994 period because of the increasing importance of disproportionate contributions. By examining degradation processes across several scales, we believe that the interactions of salient social and biophysical dimensions continue to drive the system with infrequent but large pulses of P such that annualized averages appear to be stable across time. In this setting we found evidence of disproportionality driven by variables operating on both short and long temporal scales. There was evidence of disproportionality in our examination of developmental processes at the watershed scale, as well as in our examination of risk of P loss at the field scale.

The concept of disproportionality has several implications for scientists working in interdisciplinary settings investigating natural resource or environmental issues. First, it emphasizes the need for this interdisciplinary scholarship to occur in an interactive rather than additive fashion. As stated earlier, the meaning placed on

any social behavior is highly dependent on the specific biophysical setting where it occurs. Identical behaviors can have very different implications in the same fashion that disparate behaviors can have similar environmental consequences. The mantra of good science, "It depends," is an essential dimension of the concept of disproportionality. Application of this concept to other settings should also assist social scientists attempting to develop interdisciplinary partnerships. Biophysical models of environmental degradation are too often driven by a characterization of average or recommended social behaviors. While understanding the implications of these modal behavioral patterns is important, the concept of disproportionality warns us that it is the exceptional or the outlier in both the social and biophysical realms that may drive the output of the system being investigated. Disproportionality increases the probability of a situation in which "the tail wags the watershed," as noted by William Freudenburg, currently the Dehlsen Professor of Environmental Studies at the University of California in Santa Barbara (W. Freudenburg personal communication 2000).

The second implication of the concept of disproportionality is related to the design and implementation of resource management policy. If the goal of policy is to be effective and efficient, then specifically addressing the concept of disproportionality has the potential to achieve greater marginal rates of return in environmental benefits (Nowak and Cabot 2004). If this is the case, then this calls into question the design of voluntary and regulatory resource management programs. An example of this caution is in the area of soil and water conservation programs. There is an extensive body of literature that argues that voluntary soil conservation programs are ineffective in addressing environmental problems (Classen et al. 2001; Napier and Johnson 1998; Trimble 1985). Rural sociologists have argued that voluntary information and education efforts fail to induce the adoption of conservation practices (Napier et al. 2000). The core logic underlying these critiques is that policies are deemed ineffective when the cumulative impact of the behavioral changes that are induced through implementation of the voluntary program does not significantly change the associated environmental impact. However, the case of disproportionality suggests a few outliers in the program's jurisdictional area can determine the overall impact of the voluntary program on the environmental system. This suggests that resource management programs need to pay less attention to "average" behavior, and focus more attention on "exceptional behavior." If the statistical tails are indeed "wagging the watersheds," then intervention efforts need increased attention to the few inappropriate behaviors that occur in vulnerable settings or times. We acknowledge that the concept of targeting has been tried since the late 1970s when multistate regions were initially targeted for soil conservation. More recently, we see entire watersheds being targeted for programmatic intervention based on the U.S. EPA definition of total maximum daily loads. Yet in all of these efforts, the lack of attention to a nuanced, scalar analysis of social–biophysical interactions has caused program managers to ignore potential disproportionate contributions that may be driving the output of the system. Most resource management "targeting" efforts continue to focus on averages within large-scale geographical areas. Who adopts, an interesting question in the classic adoption and diffusion of innovations model (Rogers 1995), or why they adopt, a more theoretically rich question, may not be as important as exploring where and when this behavior occurs or needs to occur. This will require accounting for the scale-specific biophysical setting of that behavior. In turn, this implies that any natural resource management program that strives

for effectiveness and efficiency needs to be based on an interdisciplinary partnership of social and biophysical scientists.

Conclusions

Early social science was influenced by the work of Adolphe Quetelet, who promoted the idea that the average in a normal distribution represented the "essence" of a social system whereas variance or outliers were viewed as "accidents" in the study of social processes (Kruger et al. 1990). Charles Darwin, on the other hand, viewed variance, or the outlier, as central to understanding evolutionary biological processes. In this article, we have argued that giving more attention to variance across multiple scales can serve as a conceptual bridge between the social and biophysical sciences. Disproportionality is a concept that can bridge disciplines by focusing on the salient interactions between humans and their environments at different spatial and temporal scales.

A more robust test of the disproportionality concept is needed in other areas of natural resource management, a task beyond the logistical capabilities of the NTL-LTER. We have tried to tell a story about how disproportionality is occurring at different spatial and temporal scales in the Pheasant Branch Creek subwatershed of Lake Mendota. This story provided some insights as to why long-term P loadings have remained relatively stable, while the social "drivers" have changed significantly.

Perhaps the most important contribution made by this adaptation of the disproportionality concept is that it reaffirms the importance of true interdisciplinary research. While skewed data distributions are common in all sciences (Limpert et al. 2001), unilateral disciplinary approaches will not discern and address disproportionality, which emerges from the *interaction* between outliers in the social and biophysical realms at different spatial and temporal scales. Testing for disproportionality in the natural resource management arena is dependent on addressing a scale-specific interaction of variables in both the social and biophysical sciences. Currently, however, interdisciplinary research, the context in which the methodologies and concepts needed to more robustly identify and measure disproportionality will be developed, is a fragile and informal collaboration with weak institutional support (Daily and Ehrlich 1999). There are a few reasons why this is so. First, the value placed on interdisciplinary collaboration is largely dependent on the individual researcher (Naiman 2000). Second, interdisciplinary collaboration is not part of the typical graduate student education, so future interdisciplinarians find themselves at odds with traditional university structures (Nissani 1997; Golde and Gallagher 2000). Finally, the formation of interdisciplinary collaborations is predicated on each collaborator acknowledging that his or her discipline carries its own "blind spots" (Freudenburg and Alario 2000). The NTL-LTER program has overcome many of these constraints and blind spots, and our hope is that our colleagues in natural resource analysis will begin to develop innovative applications of the concept of disproportionality in a true interdisciplinary setting.

Notes

1. The term *load* refers to the mass of phosphorus being delivered during a fixed time period, typically 1 day. This is distinguished from *concentration*, which refers to the mass of phosphorus being delivered within a fixed runoff volume.

2. Independent in the sense that the social processes, development, do not consider that there is a "location" to the biophysical characteristics (P levels) that will influence the outcome of this process. See Goodchild and Janelle (2004) for a complete explanation of this concept.

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