INEQUALITY IN THE CREATION OF ENVIRONMENTAL HARM: LOOKING FOR ANSWERS FROM WITHIN

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ABSTRACT

To date, many environmental policy discussions consider inequalities between groups (typically by comparing the average or aggregate resource use of one group to another group), but most ignore disproportionalities ***within groups****. Disproportionality, as discussed in a small but growing body of work, refers to resource use that is highly unequal among members of the* ***same*** *group, and is characterized by a positively skewed distribution, where a small number of resource users create far more environmental harm than "typical" group members. Focusing on aggregated or average impacts effectively treats all members of a group as interchangeable, missing the few "outliers" that actually tend to be responsible for a large fraction of overall resource use. This chapter offers reasons why we should or should not* ***expect*** *disproportional production of environmental impacts (from both mathematical and sociological perspectives), looks at empirical evidence of disproportionality, and offers a framework for detecting disproportionality and assessing just how much difference the outliers make. I find that in cases*

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where the within-group *distribution of resource use is highly disproportionate (characterized by extreme outliers), targeting reduction efforts at the disproportionate polluters can offer opportunities to decrease environmental degradation substantially, at a relatively low cost.*

BACKGROUND

In *State of the World 2006*, Worldwatch Institute asks if there is enough "ecological capacity" for everyone. The answer to this question, in their account, depends on how many resources are consumed by the average world citizen, which, in turn, depends on the average consumption rate within each country. Resource consumption is measured in global hectares, using a technique called Ecological Footprinting (Wackernagel & Rees, 1996). The Ecological Footprint attempts to quantify the amount of resources needed to support an economy by converting the types and quantities of resources used for food, housing, transportation, consumer goods, and services into a single number (the amount of biologically productive land), called the "footprint" of the economy. Worldwatch Institute addresses the vast inequality of resource consumption (footprints) between more and less developed countries as follows:

> The unequal claims on biocapacity become clear when they are analyzed on a per person basis. The average Indian or Chinese footprint is well under the world average of 2.3 global hectares. In contrast, the average Japanese and European each required roughly 4.5 global hectares to support their lifestyles. And the average American is in a separate league entirely, with a footprint of 9.7 global hectares. (Flavin and Gardner, 2006, p. 16)

Importantly, these disproportionate footprints are expressed in terms of demand "per person," or "by each person," but in fact, they actually represent the aggregate, or *total* environmental impact in each country, divided by the number of people in that country (known as the "average" or "arithmetic mean"). The Ecological Footprint is often used for this type of coarse, national-level comparison, because "consumption, production, and trade data are generally compiled at the national level by domestic statistical offices," while "data specific to lower-level political entities such as states, provinces, or cities are generally much harder to come by" (Marcotullio & McGranahan, 2005, p. 817). Still, when measures of resource consumption are aggregated in this way, one of the key stories of consumption inequality fails to be revealed – the story of *within-group* variation. As the following pages will spell out, recent research suggests that this kind of focus on "average" or "total" amounts of resource use paints an inaccurate portrait of how much resource consumption is "necessary" to support a certain standard of living, often *overestimating* the amount of consumption that is associated with a "typical" person, sector, or industry within an economy.

This analysis is presented in four main sections. First, I provide a review of how the resource efficiency of an economy has been characterized in mainstream literature. Next, I draw on sociological and statistical theories to explore whether or not we should *expect* disproportional consumption of resources. Third, I trace the roots of Disproportionality Theory, first proposed by Freudenburg (1997) and Freudenburg and Nowak (2000), and examine empirical evidence, noting that where the *within-group* distribution of resource use is highly disproportionate (characterized by extreme outliers), targeting reduction efforts at the few disproportionate polluters offers an opportunity to decrease resource consumption substantially, at a relatively low cost. Finally, I consider how much of a difference "outliers" make when within-group disproportionality exists, and provide an approach for detecting instances of large inequalities within groups more systematically.

RESOURCE CONSUMPTION: GETTING THE NUMBERS RIGHT

Footprint analysis provides a useful starting point for characterizing resource consumption, but the metric can hide important variations within groups. Just as narrowly focusing on the "world average of 2.3 global hectares" fails to reveal the vast inequalities in consumption rates *between* nations, narrowly focusing on a "United States average of 9.7 global hectares" omits crucial information about the vast inequalities *within* the United States. Preliminary research indicates that within-group inequality of resource consumption (in this case, inequalities within specific countries) may be even greater than between-group inequality (in this case, the inequality between countries). A growing body of research suggests that within-group inequality in resource consumption (whether it be "within-country," "within-industry," or "within a specific sector of an industry where firms are producing comparable and relatively homogeneous products") is characterized by a few actors that are responsible for disproportionately large shares of the resources being used or of the pollution being generated (Freudenburg, 2005, 2006; Nowak & Cabot, 2004;

Nowak, Bowen, & Cabot, 2006). The resultant implication is that focusing on the mathematical "average" tends to *overestimate* the amount of resource use that "typifies" the majority of the people or firms in each group.

This difference between "average" and "typical" may be obscure. According to Webster's New World Dictionary, "average" has two distinct meanings. One is "the numerical result obtained by dividing the sum of two or more quantities by the number of quantities; an arithmetical mean," while the other is more broadly "the usual or normal kind, amount, quality, rate, etc.," or "a number or value that typifies a set of values of which it is a function, as a median or mode (Guralnik, 1986)."

In some cases, the first or mathematical definition of "average" (arithmetic mean) can be roughly equivalent to the notion of "average" being a typical, or representative measure of group performance, but that will not always be the case. If all members of a group consume exactly the same quantity of resources (for example, if each person in the United States were to consume 9.7 global hectares), the "average resource use" would be equal to the "per capita resource use" for every single member of the group. Thus, all members of the group are "interchangeable." In this case, the impact of each member of the group truly would be proportional to the group's total resource consumption divided by the number of members (see Case A, "within-group Proportionality" in Table 1), and using the "arithmetic mean" would accurately reflect the "normal amount" of pollution for the group. However, if within-group consumption is not equal, that is, group members are not "interchangeable" in their consumption rates, the mean may not typify the set of values (see Case B,

Table 1. Hypothetical Distributions of Resource Use among Five U.S. Citizens.

United States Citizen	Ecological Footprint (Global Hectares)	
	Case A: Within-group Proportionality	Case B: Within-group Disproportionality
Citizen #1	9.7	1
Citizen #2	9.7	2
Citizen #3	9.7	2.5
Citizen #4	9.7	3
Citizen #5	9.7	40
Average footprint	9.7	9.7

"within-group Disproportionality" in Table 1). Consider the following hypothetical consumption rates for five United States citizens:

Even though the "average" footprint is the same (9.7 global hectares) for both distributions of resource use in Table 1, the average is far from the "normal" amount of consumption for the Disproportionate case. In this hypothetical example, all citizens but one actually consume far *below* the mean for the group. This example illustrates the statistical concept of a "positive skewed distribution" (an asymmetric probability distribution characterized by a long tail on the right side), as just one person (Citizen #5 in Case B) is responsible for a disproportionate impact on the average consumption for the group.

In statistics, the problem of an "outlier" (a value far away from the center of the distribution) influencing the average of a distribution can be resolved by avoiding the use of the mean, and instead using the median (which is the "middle" number in a group when values are arranged in ascending order, and a more robust measure of central tendency for skewed distributions). For the example set of values, the median is 2.5 global hectares, which is much more "typical" for the five citizens than the value of 9.7. However, simply replacing the mean with the median still fails to draw attention to the most important part of the disproportionate distribution, the single citizen who consumes 40 of the 48.5 global hectares (which is the total consumption for all five citizens in this hypothetical example). Importantly, without actually examining the distribution of resource consumption within each group, the citizens in the Proportionate distribution appear to consume the exact same amount of resources as the citizens in Disproportionate distribution. Clearly, reporting "per-capita" consumption can greatly overestimate the "typical" resource use for disproportionate distributions. In the next section, accordingly, I explore commonly accepted methods for characterizing societies' resource consumption, which are likely to misrepresent the "normal" amount of resource consumption when the underlying distribution is disproportionate.

RESOURCE CONSUMPTION: TENDENCY TO FOCUS ON BETWEEN-GROUP INEQUALITY

The use of the "average," "per-capita," and/or "total" amount, in describing resource consumption, is so pervasive that this author was hard-pressed to find analyses that did *not* employ one or more of these measures. Recent efforts to characterize the exploitation of planet Earth's resources and ecosystem services, such as the *AAAS Atlas of Population and Environment* (Harrison & Pearce, 2001), *Living Planet Report, 2006* (World Wildlife Fund, 2006), and *State of the World, 2006* (Flavin & Gardner, 2006) all report both per-capita and total resource consumption between nations; the latter two publications explicitly use the technique of Ecological Footprinting.

The Ecological Footprint (Wackernagel & Young, 1998) embodies the same basic principles as the "IPAT" model developed 27 years earlier by Paul Ehrlich and John Holdren (Ehrlich & Holdren, 1971), which was later subjected to several revisions and refinements, such as the "STIRPAT" model by York, Rosa, and Dietz (both of which will be discussed below). Both models use three parameters to characterize the resource consumption of a group: the size of the population, the per capita consumption, and the "intensity" of the consumption (which is often considered to be a function of available technology – see Fig. 1 below)

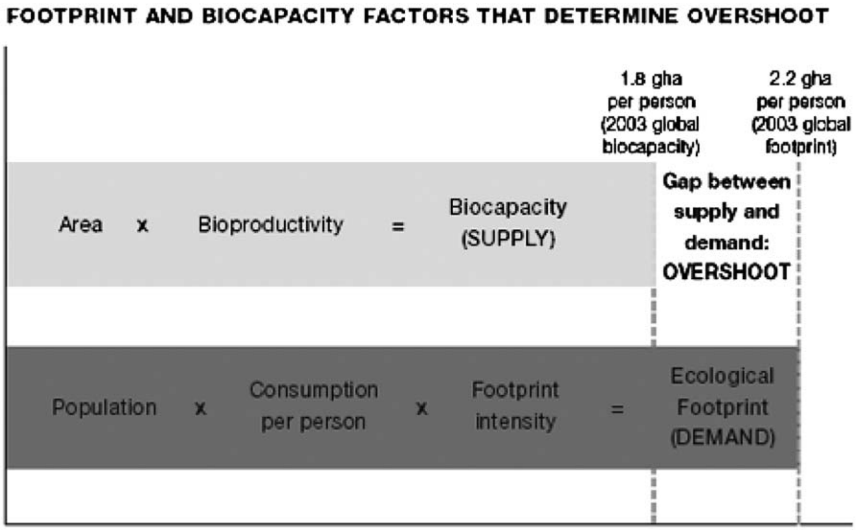

Fig. 1. "Footprint" of Resource Consumption (demand) is Based on Three Parameters: Population, Per-capita Consumption, and Footprint Intensity. Notably Absent is any Measure of the Variance in Per-capita Consumption (World Wildlife Fund, 2006).

The Ecological Footprint measure permits a simple, straightforward comparison of one group (usually a nation, though the methodology has been applied to sub-national scales, for example, see Wackernagel, 1998) against another group, as well as allowing comparison of the resources required by an economy to the resources available to that economy. The "economy" is treated as one homogenous entity, with the "footprint" of the economy often expressed on a per capita basis (by dividing the total footprint by the population of the economy). When this accounting tool is used to compare resource use between groups, it implicitly ignores any inequalities *within* an economy.

Similarly, the "IPAT" formula, proposed by Ehrlich and Holdren in the early 1970s (Ehrlich & Holdren, 1971) is a frequently used model for conceptualizing environmental impacts resulting from economic activity. The simple formula, I = PAT, is used in many introductory texts on Environmental Studies (for example, Miller, 1998, p. 16), and it provides the underlying principle for a vast body of literature on society–environment relationships (Commoner, 1972; Ehrlich & Holdren, 1971; Chertow, 2001; York, Rosa, & Dietz, 2003). According to the IPAT model, a society's environmental "impact" (I) is the product of its "population" (P), multiplied by its "affluence" (A), by its "technology" (T). Population means "overall number of people," while affluence is typically measured in dollars (of GDP or GNP) per capita. The "technology" term, which is designated as "environmental degradation and pollution per unit of resource used," in theory is intended to account for the ecological efficiency of industrial processes. In practice, however, "technology" is rarely measured, and is often used instead to represent "everything else" that population and affluence cannot account for (Chertow, 2001). Importantly, the limited efforts that have been made to put actual numbers into the IPAT equation still rely on a single value for all three factors. Specifically, the model relies on *average* values for both "affluence" and "technology," resulting in the same potential bias as the Ecological Footprint model. For societies where a small fraction of the population consumes many more resources or produces much more pollution than other members, the IPAT model fails to communicate the vast differences in resource consumption that exist within groups.

Even refinements continue to display this difficulty. When the "IPAT" model was revised by York et al. (2003) to "STIRPAT" (STochastic Impacts by Regression on Population, Affluence, and Technology), for example, those authors chose to account for random effects by introducing an "error term." The authors rewrote the model as $I_{\mathrm{i}} = aP_{\mathrm{i}}^{b}A_{\mathrm{i}}^{c}T_{\mathrm{i}}^{d}e_{\mathrm{i}}$, where the coefficients a, b, c, and d can be estimated by regression analysis. Unfortunately, the final estimated model stills relies on average values for affluence and technology, and thus makes no improvement its ability to prevent outliers (such as the fifth U.S. citizen in the simple model presented earlier in this chapter), from influencing what are taken to be typical, normal, or representative values.

One simple step toward resolving the potential bias present in both the Ecological Footprint method of accounting and the IPAT or STIRPAT models would be to use median values instead of means (see discussion in "Getting the Numbers Right" section). While this approach would markedly improve the accuracy of the models in comparing the "typical" impact of one society to the "typical" impact in another society, the models would still focus attention to the middle of the distribution, rather than the "tail," which is where we can expect to get the leverage for pollution reduction efforts. Before changing widely accepted models, and insisting on inspections of resource consumption distributions, it is pertinent to review theoretical perspectives from sociology, in conjunction with mathematical principles, on why we should, or should not, *expect* distributions to be disproportional.

SOCIOLOGY MEETS STATISTICS: SHOULD WE EXPECT DISPROPORTIONALITY?

A key question in the sociological literature, in the late 1970s and 1980s, was whether relationships between the environment and the economy were characterized by "inherent conflict." According to the "core" literature of environmental sociology, economic growth is expected to be associated with greater environmental harm (for a relatively recent assemblage of summaries and further reviews, see the *Handbook of Environmental Sociology* (Dunlap & Michelson, 2002)). By the 1990s, on the other hand, several bodies of work (largely of European origin) began to express nearly the opposite expectations, emphasizing hypothesized *environmental benefits of economic growth*.

One relatively clear example of the "core" literature on *conflict between economic prosperity and environmental protection* is provided by the work of Schnaiberg (1980) and of Schnaiberg and Gould (1994), who argue that there is "an enduring conflict" between environmental protection and economic growth. Their work, focusing on what Schnaiberg has called the

"Treadmill of Production," is based on the argument that economic producers need ever-increasing profits, which they attempt to achieve by means of ever-growing production, leading in turn to ever-increasing environmental impacts. Similar expectations are evident in later work on what O'Connor (1988, 1991) (see also Foster, 1992) has called "the second contradiction of capitalism." In essence, O'Connor sees capitalism as relying on prosperity for legitimatizing economic expansion, creating a need for ever-increasing exploitation of the environment. If the work of Karl Marx (Marx, Moore, Aveling, & Engels, 1889) on "the first contradiction of capitalism" involves the exploitation of workers in the search for producer profit – to the point where the workers are unable to buy the products – O'Connor proclaimed that "the second contradiction" involves such heavy exploitation of natural resources that nature, too, can no longer support the continued survival of capitalism. Under the expectations of the "core" literature, the fundamental conflict between economic activity and environmental welfare *necessitates* environmental destruction, and this *necessity* should explain the observed environmental degradation associated with an economy. Thus, we should expect relatively uniform amounts of "environmental harm per unit of economic activity" (among producers of homogenous products). Specifically, the environmental harm resulting from each producer in the economy is expected to be proportional to its output level (this prediction corresponds to "Case A, within-group Proportionality" in the "Getting the Numbers Right" section of this chapter).

Virtually the opposite expectation – namely that economic growth can benefit the environment – is perhaps most clearly spelled out and explained in a body of sociological work on "ecological modernization," originally proposed in the German language by Huber (1985, 1991), but best-known in English-language form through the work by Spaargaren and Mol (beginning with Spaargaren & Mol, 1992). For purposes of the present chapter, the key argument of work within this tradition is that, in contrast to the relatively pessimistic views in the "core" literature of environmental sociology, environmental problems can best be solved through *further* advancement of technology, including what Spaargaren and Mol (1992) call "superindustrialization." Similar expectations are found in work on "postmaterialism" and on "reflexive modernization." Work by the best-known proponent of postmaterialism argues that prosperity leads to a greater public willingness "to make financial sacrifices for the sake of environmental protection" (Inglehart, 1995, p. 57; see also Abramson, 1997; Brechin & Kempton, 1994, 1997), and scholars within the reflexive modernization school see civil society as becoming a driving force for environmental policymaking in an age of risk. Although the underlying mechanisms are not always spelled out in consistent ways, all of these bodies of work tend to expect the widespread emergence of an "environmental state" (see Frank, Hironaka, & Schofer, 2000; but see also Buttel, 2000; Fisher & Freudenburg, 2001), overseeing the kinds of economic expansion that are beneficial to the environment. It is conceivable, under the "environmental state" theory, that differences in resource efficiencies could lead to unequal distributions of resource consumption per unit of output (whether due to some actors adopting technological advancements, as purported by ecological modernization theory, or by certain actors making financial sacrifices, as predicted by postmaterialists). None of these approaches, however, pay significant attention to the environmental implications of differing statistical distributions. In the next section, accordingly, I review statistical properties of two distributions, normal and lognormal, (both of which involve varying degrees of disproportionality) and compare their implications to the expectation of proportionality under the "core" sociological literature.

"Normal" Disproportionality

The probability density function or "distribution" in Fig. 2 is well-known and widely used throughout the social and physical sciences, perhaps

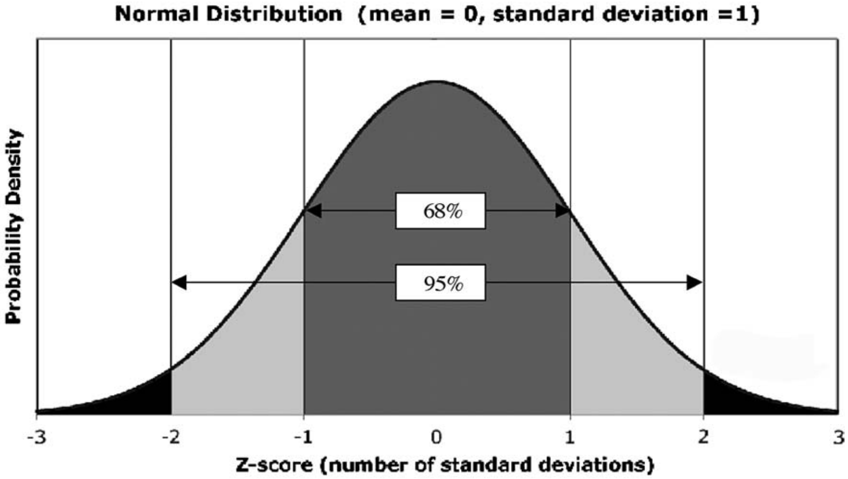

Fig. 2. 68/95% Rule for Normal Distributions.

justifying the name of "Normal Distribution," although it is also called the "Gaussian Distribution" (after Carl Friedrich Gauss) or "bell curve." Many common statistical procedures, such as *t*-tests and Ordinary Least Squares (OLS) regressions, rely on the assumption that data or error terms are normally distributed. As a quick review, a normal distribution theoretically results any time observations are influenced by many small, independent factors that are additive. For example, the distributions of physical properties of individuals in a population (such as height or weight of same sex, adult individuals) are typically well represented by a normal distribution. It seems reasonable to think that the ratio of resource use or pollution production to differing levels of economic activity might be normally distributed within an economy. However, most people would suspect that some sectors of the economy are "inherently" more polluting than others – for example, service-based sectors would be expected to pollute much less than manufacturing sectors. Within a specific industry, resource use or pollution levels among firms might be expected to follow a normal distribution, due to the combined influence of many small differences that exist among firms.

The normal distribution can be completely characterized by two measures – the average and the standard deviation (which can roughly be thought of as the "average distance of the data from the mean").[1] An important aspect of the normal distribution is that it is governed by a simple rule of thumb for predicting the degree and abundance of extreme observations, known as the 68/95% rule (see Fig. 2). This rule says that 68% of the data will be contained within one standard deviation of the mean (note: the mean is equal to the median for a normal distribution). The complement to this statement is that 32% of the data will be more than one standard deviation above or below the average. Since the distribution is symmetric, we can expect 16% of the observations to be more than one standard deviation above the mean, and 16% to be more than one standard deviation below. Similarly, the rule says that 95% of the observations will have values within two standard deviations of the average, meaning that 2.5% will have values more than two standard deviations above or below the arithmetic mean.

An important implication of the simple 68/95% rule is that we should *expect* a number of polluters to emit a disproportionate amount of pollution per unit of output (which will be referred to as the "resource efficiency" or "emissions/unit output"), when resource efficiency is normally distributed. In the case of a group of firms producing homogeneous products, the 68/95% rule would tell us that we could expect 16% of firms to emit an amount of pollution per unit of production that is more than one standard deviation above the mean. As an illustrative example, consider 100 firms in a specific industry, such as Primary Nonferrous Metal producers, within the United States. We could expect 16 of them to be polluting at levels beyond one standard deviation above normal, while about 2 of those 16 firms could be expected to pollute at levels that were more than two standard deviations above the industry average. Even if the firms were simply to be normally distributed, in other words – contrary to the way in which within-group pollution has treated to date within the "core" literature of sociology – all polluters would *not* be interchangeable. Instead, if pollution were to be normally distributed, we should *expect* to find some outliers who pollute at levels well beyond the average, while an equivalent number of firms would be equally far below the average in their pollution efficiency.

If we believe that pollution efficiency is normally distributed among firms, rather than being directly proportionate to levels of output, a pollution prevention policy that targets the "extreme polluters" could potentially decrease emissions substantially, at relatively low regulatory costs, compared to a pollution prevention policy that focused on industry-wide decreases in emissions, or one which relied on voluntary actions of polluters (for specific example, see Nowak et al., 2006, p. 169). Still, in this kind of a "normal" distribution, the ultra-efficient firms would counterbalance the highly polluting firms, meaning that the arithmetic mean of emissions/unit output would be regarded by most statisticians as a suitable measure of "central tendencies," or typical values, for the overall distribution. This property, on the other hand, is not true of skewed distributions, as is discussed below.

"Log-Normal" Disproportionality

An even more extreme form of within-group disproportionality exists when observations are log-normally distributed. The log-normal distribution has a certain resemblance to the normal distribution, but is positively skewed, as shown in Fig. 3, below. Limpert, Stahel, and Abbt (2001, p. 351) argue "… the reasons governing frequency distributions in nature usually favor the log-normal distribution, whereas people are in favor of the normal." These authors have noted any number of examples from physics, chemistry, medicine, and environmental science for which the log-normal distribution fits better than the normal distribution.

A log-normal distribution theoretically results when observations are influenced by many small, independent factors (as in a normal distribution),

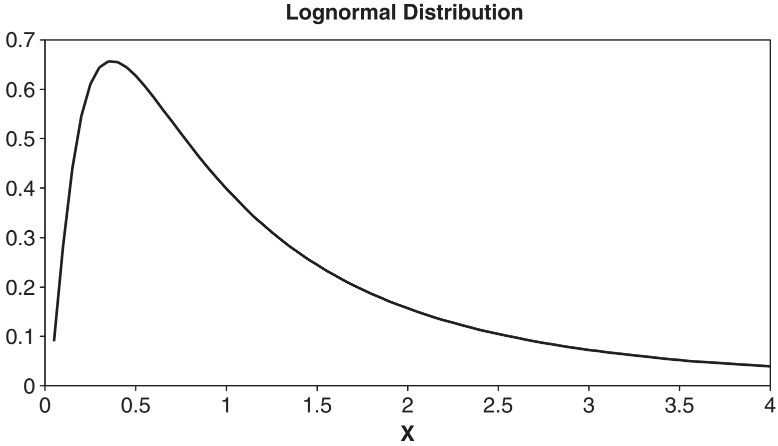

Fig. 3. Log-Normal Distribution with Median Equal to 1, and the Multiplicative Standard Deviation of *e* (2.718).

but where the "typical" observation has a low value, the standard deviation is high (relative to the mean), and the values cannot be negative, or when independent factors combine in a multiplicative fashion (rather than additively, as in a normal distribution). The log-normal distribution looks similar to a normal distribution, but the left-hand tail is truncated (it is also called a "left-censored" distribution). In terms of the distribution of pollution efficiency, values of emissions-to-output ratios can only be "non-negative," and a small but growing number of authors have presented evidence that it is reasonable to expect the typical polluter within groups to be relatively efficient, and to expect a considerable amount of variation among firms within an industry (see Freudenburg, 2005, 2006; Nowak et al., 2006).

What are the implications of a log-normal distribution? The name "log-normal" reflects the fact that taking the natural logarithm of the observations will result in a normal distribution. Since taking the logarithm "undoes" exponentiation, log-normal distributions tend to have some observations that are orders of magnitude beyond the "typical value" (which is characterized by the median, not the mean). This fact (coupled with the absence of negative values) leads to a long tail on the right-hand side of the distribution, and a large number of observations "piled up" on the left-hand side, as pictured in Fig. 3.[2] To consider emissions among polluters, let us assume a log-normal distribution of 100 polluters whose median pollution efficiency is 7.4 emissions/unit output, with a multiplicative standard deviation of 2.2 emissions/unit output. Using these hypothetical values, we find that 65% of polluters actually emit less than "average" (the mean is 10 emissions/unit output). Additionally, we can expect the top two firms to emit at least 36 emissions/unit output – almost five times as much as the "typical" polluters.

This simple discussion shows that it is worth asking whether the production of pollution is log-normally distributed; in situations where this is the case, the outliers, or highly polluting firms, could be expected to release pollutants at levels much higher than those typical of the industry. Since the average itself is highly influenced by extremes, models or assumptions that focus on the "average (mean) polluter" within an industry, or the "per-capita pollution" for the industry, will *overestimate* the central, or typical value for the vast majority of firms within the industry. Thus, it may appear that there is more pollution associated with "average" firms within an industry than would be the case if analyses were to focus on the "typical" or median firm – and our analyses may lead to policy responses (such as treating all firms as "equals") that fail to reflect the actual distribution of problems. This phenomenon may explain why polluters often argue that pollution cleanup costs are "too costly." Focusing on the "average," rather than typical, polluter could make "cleaning up an industry" appear much more difficult than it actually may be. In the following section, I review several case studies of the within-group distribution of pollution production.

BEYOND THEORY: EMPIRICAL EVIDENCE OF DISPROPORTIONALITY IN POLLUTION PRODUCTION

The United Nations Development Programme (UNDP, 1998) reports:

…Inequalities in consumption are stark. Globally, the 20% of the world's people in the highest-income countries account for 86% of total private consumption expenditures – the poorest 20% a minuscule 1.3%. More specifically, the richest fifth:

- Consume 45% of all meat and fish, the poorest fifth 5%
- Consume 58% of total energy, the poorest fifth less than 4%
- Have 74% of all telephone lines, the poorest fifth 1.5%
- Consume 84% of all paper, the poorest fifth 1.1%
- Own 87% of the world's vehicle fleet, the poorest fifth less than 1%

These well-known statistics are part of a large and growing body of work on "environmental justice," (summarized elsewhere in this volume by Bullard, in press; Mohai, in press; Taylor, in press; see also Boyce in press; Harlan et al., in press), which explicitly addresses the potential inequities in the environmental impacts *experienced by* different social groups. Only recently, however, have sociologists and physical scientists began to explore potential widespread inequities in environmental impacts *created* by *social* factors within groups.

In the 1990s, interdisciplinary work began on a pair of projects supported by the National Science Foundation (NSF) at the University of Wisconsin-Madison (one a Long-Term Ecological Research (LTER) Project and the other a newer program of Integrative Graduate Education and Research Training (IGERT)) focusing on "Lakes and Society." The projects brought together a number of researchers, including Steve Carpenter, Bill Freudenburg, and Pete Nowak, the latter two of whom would go on to lay the foundation for the concept of "disproportionality" as a pattern that bridges the physical and social sciences. Steve Carpenter, the lead PI on the LTER, is an ecologist who was interested in species-abundance trends, among other phenomena. As he discussed with Nowak and Freudenburg, studies of species-abundance patterns commonly found a log-normal pattern, where many species occurred with low abundance, and very few species occurred with high levels of abundance.

Professor Freudenburg (1997) had by that time begun to argue that sociological work on the environment should pay greater attention to the firms putting out the highest levels of pollution, but discussions with Professor Carpenter led both Professors Freudenburg and Nowak to discuss the extent to which the notion of log-normal distributions might provide a useful framework for describing the patterns that had been emerging in their studies of environment–society relationships.

Both Freudenburg and Nowak had by that time reached the conclusion that the broader "economy vs. environment" debate (see "Sociology meets Statistics") was in effect *too* broad. In their view, and in the view of several social scientists working with them on the NSF projects (see especially Fisher & Freudenburg, 2001, 2004; Nowak et al., 2006), the available empirical record included a number of cases that appeared to be at least reasonably consistent with the expectations being expressed on both sides of the broader, or macrosociological, divide. The irony, of course, is that if both "sides" have offered empirical evidence for their own perspectives, then neither side could be completely or consistently correct. Freudenburg and Nowak had thus both become increasingly interested in examining specific cases of environmental harm that might throw light on *the extent to which* any given case of environmental harm might actually be "necessary" for (and therefore proportionate to) economic output, providing insights on *the conditions under which* one point of view or the other might be likely to be more accurate.

In his own research on toxic releases, in particular, Freudenburg (1997) had noticed that certain sectors of the economy produced dramatically more toxic releases than others, whether the releases were measured in terms of raw pounds or in terms of toxicity. Even within a specific industry or sector of the economy, certain firms had emissions levels well beyond the "average" level for the industry or sector in question – and those differences were evident even after accounting for the size of the facilities, in terms of either number of employees or output of products.

Freudenburg reports that he had previously noted that the levels of pollution within specific industries tended to look vaguely log-normal in their distributions, but that it was the casual conversation with Steve Carpenter, followed by more intensive conversations with Pete Nowak, that helped to crystallize his thinking. In a series of papers, Freudenburg and Nowak (2000) (see also Freudenburg, 1997, 2005, 2006; Nowak & Cabot, 2004; Nowak et al., 2006) postulated that "disproportionality" between economic activity and environmental harms (e.g., toxic releases) needed to be examined as a variable that could be used to move the social science literature on environment–society relationships beyond broad or black/white assertions. Examining actual levels of disproportionality, to be more specific, could allow researchers to measure the extent to which economies (or specific economic industries or sectors) could *appear* to be at odds with the environment (as predicted by the "core" works of environmental sociology) – at least when measured by mean or aggregate levels of pollution – even though the *majority* of firms in that industry or sector might support the idea of compatibility between the economy and the environment, being responsible for much lower levels of environmental degradation than the mathematical average for their own industries or sectors.

To quantify the levels of disproportionality in toxic releases, Freudenburg (1997) began with the Environmental Protection Agency's (EPA's) Toxic Release Inventory for the year of 1993 – one of the first years to become widely available to researchers in CD-ROM format. In an effort to communicate his results to the research community, Freudenburg (2005) ultimately utilized the Gini coefficient, a measure of inequality that has been widely used to describe the degree of inequality in a society's wealth, or incomes. Values for Gini coefficients range from zero to one, with zero describing a society having perfect equality – one in which incomes (or pollution) are spread equally among all persons (or facilities) – and a value of one describing a society of perfect inequality, in which one person (or facility) is associated with 100% of the income (or pollution), and all other persons (or facilities) have no income (or pollution). As noted by Freudenburg (2005, p. 96),

> In practice, coefficient values range from around .2 for historically equalitarian countries such as Bulgaria or Hungary to around .6 for nations where powerful elites dominate the economy, with the world's highest coefficient today being associated with Sierra Leone, at .62. Most present-day European countries and Japan range from around .25–.32, while most African and South American countries – and in recent years, the United States – have had Gini coefficients in the range of .45–.50

Using the same coefficient for analyzing inequalities in levels of toxic emissions, Freudenburg found that, even when data were compared only across the seven industries that made up the most toxic industrial sector of the U.S. economy – Standard Industrial Classification (SIC) category 33, Primary Metals – the disproportionality levels were higher than in any national study he had ever encountered. South Africa, during the era of Apartheid, had been found to have a Gini coefficient of 0.71, but the Gini coefficients for disproportionality of emissions were consistently higher, even after controlling, statistically, for the differing size of one industry vs. another. After controls were imposed for the sizes of payrolls and for the number of employees, "the Gini coefficients actually became even more extreme, rising to 0.817 and 0.821, respectively." Sharpening the focus ever further, and comparing the 62 enterprises or facilities within the most toxic sector (SIC 333, or Primary Nonferrous Metals), Freudenburg (2005, p. 100) found that

> Rather than becoming more even, the results become even more disproportionate, leading to a higher Gini coefficient than this author, at least, has ever encountered in any other context: .975. So disproportionate are the emissions from this sector, that a single facility – Magnesium Corporation of America, in Rowley, Utah – accounted for more than 95 percent of the toxicity emitted from the entire 333 SIC code, or for that matter, roughly 75 percent of the toxicity associated with the riskiest two– digit sector of the entire economy. Although this facility may indeed be an "outlier" in many respects, in short, it produces such a high level of toxic emissions that this single facility has more influence on the overall levels of toxic emissions from this sector of the economy than do all other facilities in the same sector, even in combination.

The firm size and output could not be controlled statistically at the facility level of comparison, due to lack of data availability, but rather than seeing this facility as being an unusual case that should simply be ignored, Freudenburg began to describe such facilities as being better understood as examples of what another paper (Berry, Freudenburg, & Howell, 2004) called "the tail that wags the distribution." Still, to investigate whether or not the Magnesium Corporation of America might be an anomaly, Freudenburg recalculated the Gini coefficient for the remaining 61 facilities in the industry, finding that, as would be expected, the resultant 61-facility comparison did show a decline in the Gini coefficient, although that decline was "only back to the same general range seen in the earlier Gini coefficients of this chapter, or 0.735 – a coefficient that still remains above the levels of income inequality associated with South Africa during the time of apartheid, as well as being substantially higher than the coefficient for income inequality in any nation of the world today."

Freudenburg's research, although exploratory in nature, has presented convincing evidence that remarkably high degrees of disproportionality have gone unnoticed, and that focusing on aggregate measures of environmental performance (such as averages or totals) misses both the disproportionate polluters that create a substantial fraction of all damage *and* the majority of firms, which are polluting less than the average or mean.

The work by Freudenburg's colleague in Madison, Pete Nowak, has developed complementary findings while working on a very different kind of pollution problem. In research that tied in with his collaborations with Professors Carpenter and Freudenburg, Nowak has long been studying phosphorus (P) loading within the Pheasant Branch Creek Watershed of Lake Mendota, near Madison, Wisconsin. His research addressed the question: "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 [phosphorus] loads to the lake?"

Nowak observed patterns of disproportionality in the relative impact of polluters, at various scales of analysis, which were strikingly similar to Freudenburg's findings. In the case of Lake Mendota, however, Nowak has found that the key determinants of the impact of human actions on the ecosystem involved the biophysical properties of the environment, *in combination with* inappropriate social behaviors. Nowak's key findings involved what he and his subsequent colleagues have called "coarse-scale" and "fine-scale" disproportionality, where "coarse-scale" disproportionality involved long-term spatial and temporal differences in P loading in the Pheasant Branch subwatershed, and fine-scale disproportionality involved phosphorous levels within individual agricultural fields, as measured in a shorter time period.

> 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 … (Nowak et al., 2006, p. 161)

> 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 & Nowak, 2005) … . The majority of the soil test results are in the high or excessively high range for P values, with a clear sub-set of outliers that have values up to 900% above the sample mean. (Nowak et al., 2006, p. 166)

From these findings, Nowak et al. take issue with the tendency to describe the outliers as "bad actors," concluding instead that "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 time. 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." (Nowak et al., 2006, p. 158).

Nowak and his colleagues have effectively combined the disproportionality among social actors within a group (as found in Freudenburg's research on toxic releases) with inequities known to exist in biophysical phenomema (as found in biological work on species abundance curves) and processes (such as nutrient export and soil loss). His analysis highlights a type of reasoning called "systems thinking," which postulates that a system cannot be understood by reducing it to (and understanding only) its parts. Instead, understanding synergies between social actions and biophysical settings is necessary to predict and explain environmental outcomes.

The pioneering work of Carpenter, Freudenburg, and Nowak suggests that the patterns of disproportionality in the *creation* of environmental damage have largely gone unnoticed and/or taken for granted in past analyses of people and the environment. Their early results show that tangible, and often very serious outcomes, such as toxic pollution and degradation of land and waters, can be highly influenced by a few "outliers." Outliers, by definition, are associated with values far away from the norm, but just how far from "typical" are they? When polluters are not interchangeable, it is pertinent to question how much of the pollution is a result of small number of heavy polluters, which is the topic of the next section.

THE TRAGEDY OF THE COMMONS: HOW TO MANAGE A NOT-SO-"COMMON" PROBLEM

Hardin's classic (1968) *Science* article, "The Tragedy of the Commons," paints a portrait of a society that allows unrestricted access to a common (shared), yet finite pool of resources (in Hardin's example, the limitation is the biological carrying capacity of the commons). In Hardin's imagined society, based loosely on the English grazing "commons," each profit-seeking individual will have incentive to exploit more and more of the pasture. Doing so imposes an external cost on other grazers, and ultimately degrades the commons. Hardin uses the example of cattle grazing on a pasture, where the pasture is the shared resource, and each individual derives private benefit from adding another cow to the pasture. The "cost" associated with an additional cow's grazing (once the carrying capacity of the system is exceeded) may come in the form of depletion of grass, soil compaction and subsequent loss, and removal of nutrients, but these costs are spread among all of the society's pasture-sharing members. Thus, if a person adds another cow to the pasture, s/he derives sole benefit from the addition, but only pays a fraction of the cost.

To Hardin, and many people living in the present-day U.S., it is intuitive that each member of the group, trying to maximize his or her welfare, will add as many cows as s/he can afford to add. If we imagine a pasture that can support only 90 cows each year, and 10 extra cows are added by "economic welfare-maximizing" individuals, the pressure from the cows added beyond the pasture's carrying capacity will degrade the pasture. Therein lies the "tragedy." The exploitation of common-pool resources is "inevitable," due to the payoffs faced by each individual. Importantly, at least in Hardin's tale, each member in the society can be seen as interchangeable, in that they all use the same decision-making logic.

Under the circumstances outlined above, a "rational manager" (or historically, the villagers who owned the cattle) would see an obvious solution of removing the 10 extra cows. The impact, under this simple example, clearly is "proportionate" to the number of cows involved, so removing 10 percent of the cows (10 out of the 100) could reduce the impact by 10 percent, bringing the number of grazers back to the carrying capacity of the pasture. Importantly, the cows are "interchangeable," it does not matter *which* cows are removed, only how many, since each cow consumes the same fraction of the pasture's carrying capacity.

In the case of toxic emissions in the U.S., by contrast, Freudenburg, Berry, and Howell (2006) found that the most heavily polluting mines or primary metals facilities did not even need to be "removed" from the economy. If instead the highest 10 percent of polluting facilities within the primary non-ferrous metals industry, for example (4 facilities out of 37 facilities in the industry for which economic data were available at the 3-digit SIC level), were simply to have reduced their emissions to sales ratio to the median level of other facilities in the same industry, the net result would have been a 83.5% reduction in the total toxic emissions for the entire industry. Even if only the *single* highest-polluting facility were merely to reduce its emissions *per dollar* to the median pollution level for that industry, over half of that industry's entire total of toxic emissions (58.2%) would be avoided.

Clearly, these preliminary findings indicate that pollution production should not be assumed to be a "Tragedy of the Commons." In this case, instead, high amounts of pollution (per unit of economic production) were actually quite uncommon. The type of scenario building described above (where the pollution efficiency of the highest polluting firms within an industry are decreased to the median level of the group) may offer a useful starting point for understanding how much of a difference the disproportionate polluters make.

Research on disproportionality is still at a sufficiently early stage that it is not possible at present to say whether such reductions are higher, lower, or about average for the kinds of environmental improvements that could be obtained in other sectors of the economy. Still, even if the case of this one sector of the economy proves to be relatively extreme, it is clear that focusing more attention on "outliers" can provide opportunities to reduce pollution at a lower marginal cost than policies that are focused on the "average" polluter.

Under conditions of disproportionality, simply blaming the pollution problems of an industrialized economy on the "average" individual is not only inaccurate, but is badly misleading. In fact, using the average not only misses the "outliers" – the firms that are responsible for the lion's share of the harm – but it also distracts attention from the vast majority of actors who are able to produce goods at pollution levels significantly below the mean. Future analyses need to pay attention not only to "how much" pollution, but also to "who" is polluting "how much." From a pollution policy and management perspective, it is imperative to be able to detect disporportionality.

DETECTING DISPROPORTIONALITY: GOODNESS-OF-FIT STATISTICAL TESTS

Future research on disproportionality will be most effective if the detecting of log-normal distributions – those that are characterized by a few outliers that skew the mathematical average – is "operationalized." One promising option for moving in that direction, is the use of statistical "goodness-of-fit" tests, which allow the researcher to test whether the data come from various distributions (such as normal or lognormal ones).

A useful starting point for this topic involves the fact that the expectations of the various sociological theories of society–environment interactions (reviewed in the "Sociology meets Statistics" section of this paper) can be tested using statistical goodness-of-fit tests. Under the expectations of the "core literature," which predicts a fundamental conflict between economic activity and environmental welfare, environmental harm should be proportional to economic activity. If we allow for small and unrelated random effects to contribute additively to the amount of toxic releases per unit output among firms in an industry, then the probability distribution might be expected instead to be roughly normal (Gaussian distributed). Finally, the growing body of new evidence, suggesting the existence of considerable disproportionality, would cause us to expect the probability distribution of environmental harm per unit of economic activity to be positively skewed, with a small number of economic actors accounting for the largest inputs of environmental pollution per unit of economic activity. Table 2 summarizes the distribution that would be expected under each hypothesis.

In general, all goodness-of-fit (GOF) tests use the same null hypothesis – namely, that the data are sampled from a specified distribution. The test statistics report the probability of findings that deviate as much, or more, from the observed sample data, if the null hypothesis were to be true. The tests differ in how they quantify the deviation of the observed sample distribution from a specified distribution. Preliminary results (Berry, Freudenburg, & Howell, 2005) indicate that, for eight different ways of examining toxic emissions (at the 3-digit SIC code level of analysis, controlling for economic output), the normal probability distribution was rejected (at a 0.0001 significance level) in every case. By contrast, in seven

Table 2. Expected Distributions Under Various Sociological Theories. The Author Recommends Using the D'Agostino–Pearson Goodness-of-fit Test to Characterize Distributions (D' Agostino, Berlanger, & D'Agostino, 1990).

Hypothesized Relationship between Environmental Harm and Economic Activity	Sociological Theory	Expected Probability Distribution
Proportional (linear)	"core" literature	None: one value characterizes all polluters (pollution necessary to produce good/unit output)
Proportional + random effects	"core" literature, relaxed (largely unexamined in literature to date)	Normal
Disproportional, positively skewed	Largely unexamined, but expected in disproportionality literature and potentially compatible with ecological modernization	Lognormal

out of the eight cases, the log-normal probability distribution could not be rejected. Interestingly, in the one case where the lognormal distribution was rejected, it appeared that the data was skewed too far to the right – that is, the highest polluting facilities were even more extreme than would be expected even from lognormal distribution.

GOF tests provide a straightforward method of detecting disproportionality, but, more importantly, examining the distribution of pollution production permits the researcher to notice "who" is responsible for "how much" of the pollution.

CONCLUSION

To portray society–environment relationships accurately, and thus to enable policy makers to select effective measures for reducing pollution and environmental harm, there is an urgent need to understand the distribution of within-group resource use and pollution production. The case studies discussed in this review are still limited in number, but they tend to support the Disproportionality Hypothesis: emissions levels within a specific economic industry tend not to be proportional to the level of economic output, due to a small number of firms which pollute much more than their "fair share." Collectively, these disproportionate polluters represent an opportunity for high rates of return, in the form of pollution reduction, if policies target the outliers.

If this pattern of findings continues to be found in future research, it would mean that the widespread "Proportionality" hypothesis – the assumption that underlies most between-group comparisons of resource use and pollution production – significantly overstates the amount of pollution that is inherently associated with a given level of industrial output. It would also mean that the amount of pollution that is actually "necessary" for any given level of industrial output might be substantially lower than is the level predicted by "per capita" approaches. In cases where within-group pollution production is log-normally distributed, similarly, regulations that target highly polluting firms will likely reduce the overall pollution for an industry at a much lower cost than can be achieved by regulations that require incremental reductions from all firms.

NOTES

1. A higher standard deviation corresponds to observations that are more variable, or further spread apart from the expected value.
2. The degree to which the distribution is positively skewed depends on how large the spread of the data (measured by the standard deviation) is relative to the value of the median.

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