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Rates of environmental problem generation: Thoughts on a new research direction

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Abstract Environmental scientists are continually discovering new and emerging environmental problems. There have been many studies of how a particular environmental problem has occurred, its costs to society, and its (potential) resolution. However, to date there have been few studies of the rate at which new environmental problems are generated by human technological innovations. In this note, I present a conceptual framework that will help quantify how many now-unknown problems we may expect to occur in a given sector. Two brief case studies illustrate the difficulty of finding appropriate dataset for fitting the full model, however. Policy implications of the conceptual framework are discussed, with different kinds of economic sectors requiring different approaches.

Keywords Chemical abstracts · Environmental Kuznet's curves · Invasive species · Precautionary principle · Problem generation · TCSA

Predicting the novel

Every year, new environmental problems appear, often from unexpected sources (Worldwatch Institute, 2005). Some of these problems are resolved relatively quickly once identified, while other problems are difficult to resolve, with greenhouse gas emissions being perhaps the example *par excellence* (Bodansky, 1995). Regardless, what is most disturbing to many ecologists is not this or that environmental problem, but the sense that more and more crises arrive every year. In this paper I present some preliminary ideas on a line of research that can determine whether the rate of problem generation is truly changing over time, and can shed insight into appropriate regulatory techniques. I illustrate these ideas with two example datasets, one from the literature on chemicals and their toxicity (Levin and Kimball, 1984), and another from the literature on invasive species introduction and spread (Levine et al., 2004).

Thinking in this broad sense, not about a specific environmental issue but about the rate at which problems emerge, is difficult. At first glance, it might seem impossible to predict novel problems that have not yet occurred. However, I believe it is possible to model the rate of problem generation if two things are true in a given economic/technological sector. First, the rate at which new potential problems occur must be able to be well-defined. Second, the number of environmental problems that occurred must be possible to estimate from data.

One major difficulty in formulating such an analysis is linguistic. How one defines a problem, describes its effect, and estimates its severity necessarily varies among sectors (e.g., Gopalakrishnan and Damanpour, 1997). For example, in the case of the set of chemicals that cause atmospheric pollution, the set could

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be defined as "directly harmful to human health" (e.g., particulate matter) or "causes changes in global biogeochemical cycles" (e.g., CO_2), with radically different results. Similarly, in the case of the set of human illnesses, the set would vary if human illness was taken to mean "damaging to human well-being" versus "fatal." Moreover, how one describes the set of possible problems will also vary according to the definition. In the case of atmospheric pollution one might reasonably choose all chemicals emitted to the atmosphere in bulk, while in the case of human illness one might choose all viruses and bacteria humans are exposed to, but the details of these definitions would be more important for any particular analysis. For this paper, I define a "potential problem" as any novel technology, process, or event that might cause a problem, and a "problem" as any technology, process, or event that causes damage to the environment or human well-being. I believe that what these broad definitions lack in specificity is more than made up for by the general framework they provide for analysis.

In any economic, technological, or cultural sector during a period of time, t, the total cost to society from environmental problems in that sector, V, is:

$$V = T \times r \times C$$

where T is the number of potential problems per year, r is the proportion of potential problems that become problematic, and C is the average cost to deal with one problem. For example, T could be the number of new chemicals synthesized each year, r could be the proportion of those chemicals that are classified as harmful to human health, and C could be the average cost to the health care system to deal with one harmful chemical. To take another example, T could be the rate of introduction of non-native species into a region, r could be the proportion of those that are invasive, and C could be the average cost of dealing with any invasive plant.

One consequence of this necessary relationship is that changes over time in one of the three driving variables will cause changes in V, all else being equal. In particular, note that an increase over time in T requires a proportional decrease in r or C to maintain a constant V. One might speculate, for example, that in some sectors T will increase exponentially (that is by a constant proportion) in each time period, perhaps in line with an increase in economic indicators such as GDP (Rothman, 1998). To maintain constant V, society must insure an exponential decline, at the same rate, of either r or T.

Some of the ideas I have raised above are similar in many respects to other lines of research in the environmental economics literature (cf., Kessler and Chakrabarti, 1996). First, the implications of this framework speak to the precautionary principle (Santillo et al., 1998), which will be discussed in a later section on environmental monitoring. Second, the emission over time of particular pollutants is often addressed in studies of the environmental Kuznet's curve and its descendents (Stern, 2004). The original environmental Kuznet's curve was the unimodal relationship between nations' incomes and their emissions of a particular species of pollutant, with pollution often being greatest at middle income levels. It was later discovered that this trend only holds for some pollutants (e.g., SO_2 pollution), with other pollutants monotonically increasing (e.g., CO_2) or decreasing (e.g., fecal coliform bacteria) with income. The field has now broadened to consider the general change within a country of emissions over time with increases in wealth and technological advances (Dinda, 2004). This line of research complements nicely the more general framework I propose, and will allow a better estimate of C over time, both its mean and its distribution (i.e., the cost of a particular technology, process, or event, C_i).

While the framework I present is admittedly crude, it has the advantage of being extremely flexible. Moreover, if data is available it allows for quantitative comparisons between sectors. Finally, it offers policymakers guidance in which sectors V may rise over time, and why.

Example: Chemicals

The general framework I presented above may be clearer after examining a few example datasets. One useful example is the number of new chemicals in the world, and the attendant occasional problems with some of these chemicals (EDF, 1997). For the purposes of this example, T may be defined as the set of all new chemicals intentionally synthesized and described in the literature. r may be defined as the number of chemicals known to be harmful to human health by a government agency or agencies. C may be defined as the average expenditure by the U.S., per chemical, in dealing with its problematic effects.

Data on the number of new chemicals created each year is taken from Chemical Abstracts (Weisgerber, 1997). In many ways this dataset is one of the best for any sector for accurately measuring *T*, although there are analytical subtleties with the various classes of chemicals and chemical substances. In particular, I have excluded "organic compounds" as their numbers are far from complete in Chemical Abstracts. Data on the total number of new problematic chemicals in a year are taken from the Toxic Substances Control Act (Nabholz, 1991). There are significant problems with this dataset, as it is known not to be complete (EDF, 1997; Nabholz, 1991), and a chemical can be in the marketplace for several years or decades before its problematic nature is known and it is added. However, it is the best available data, and I believe its use is justified by the purely heuristic purpose of the present exercise.

While these results must be considered a tentative first step, pending a more thorough analysis, they are intriguing. *T* seems to be dramatically increasing, with the number of new chemicals produced every year growing exponentially, from 27,097 in 1925 to 59,098 in 1950 to 392,234 in 1975 to 725,195 in 2000. Over that time period, annual growth in the number of new chemicals on Chemical Abstracts has grown by 4.4%/yr. As the total number of problematic chemicals recorded on TCSA increases by a constant amount each year (∼2,000 chemicals/yr), our calculated value of *r* falls over time. This may simply be due to inadequate monitoring by EPA, which is chronically understaffed in this regard (EDF, 1997; Nabholz, 1991). However, it may also reflect increased efforts at screening by companies and government officials.

Example: Invasive species

Another useful example dataset may be taken from the literature on invasive species, and in particular to the excellent paper on the San Francisco Bay area by Cohen and Carlton (1998). This paper provides a relatively complete timeline of aquatic invasions over more than a century. We may define *T* as the number of new aquatic species introduced into the bay, *r* as the proportion of species that become invasive, and *C* as the average cost per invasive. Unfortunately, data on *T* is lacking, although Cohen and Carlton speculate that increased international commerce has increased the rate of introduction, implying that *T* has increased. For example, cargo tonnage at the Port of Oakland has grown by about 8.3%/yr (Port of Oakland, 1998). The total number of exotics in the estuary, as reported by Cohen and Carlton (1998), has increased at an exponential rate, from one new species every 55 weeks from 1851 to 1961, to one new species every 14 weeks from 1961 to 1995. Note that since we do not have detailed information on the rate at which *T* increases, we can not differentiate between two possibilities: *r* is falling, but less fast than *T* is increasing; or both *r* and *T* are rising over time.

The fact that there isn't sufficient data to calculate all three parameters for both of my example datasets suggests a lack of good sector-level understanding for these sectors. The author's tentative explorations of other sectors suggest that few are better understood, a situation which is indeed embarrassing for environmental scientists.

Implications for policy

The regulatory responses to a set of potential environmental problems can be loosely divided into three categories: pre-screening, monitoring, and mitigation (cf., terminology in Wood, 2003). Pre-screening is the regulatory review by which technologies, processes, or events are not allowed to come into widespread use, before they have a chance to cause any problems. Within the framework presented in this paper, *r* can be seen as having not just a mean value but a distribution of values, where each potential problem has its own r_i, which is the probability of that potential problem becoming problematic. Pre-screening aims to remove one tail of this distribution (i.e., large values of r_i), and in the process lower *r*. By necessity, this preemptive rejection of technologies, processes, or events also lowers *T*. In contrast, monitoring (the careful watching of introduced technologies, processes, and events to see which become problematic) and mitigation (the efficient reaction to problems) both attempt to reduce *C*.

As the two examples presented above show, in some systems *T* tends to increase over time. The regulatory system simultaneously may be striving to keep *V* constant, or if possible even lower it. This can be achieved by increasing the efficiency of pre-screening (which affects *T* and *r*), monitoring (which affects *C*), and mitigation (which affects *C*). Which of these strategies is most appropriate depends on the costs of increasing the efficiency of each of these methods, as well as the benefits of the full set of technologies, processes, and events bring to society. However, a few rules-of-thumb suggest themselves from the simple model presented in this paper. Systems with a relatively large T, but relatively small values of r and C, are best addressed by increased pre-screening, which effectively reduces the largest term in the equation. Systems with a relatively small T, a large value of r, and a small value of C, can potentially be addressed similarly. In contrast, systems with a relatively small T and r but large C, would benefit most from monitoring and mitigation.

An example from the real-world may help illustrate the process. Genetically-modified (GM) plants are being developed by many different companies and governments (Hails, 2000). There were 5 USDA-permitted GM plants by 1987, 587 plants by 1994, and over 6000 plants by 2000, which suggests a fairly rapidly increasing T (NRC, 2000). However, there have been few documented negative effects on human health or natural ecosystems, suggesting a relatively small r (see discussion of ecological risk in Hails (2000)). The value of C for GM plants is essentially unknown, and a subject of much speculation and argumentation (NRC, 2000). Thus in this case, all three regulatory methodologies (pre-screening, monitoring, mitigation) may be useful.

The perspective of pre-screening I describe, where technologies, processes, or events are rejected preemptively if r_i is greater than some threshold, $r_{critical}$, is at odds with that described by the precautionary principle. The precautionary principle, which states that no technology, process, or event should be incorporated into society if there are valid concerns about its safety, suggests that $r_{critical}$ should be zero (Chapman et al., 1998). From the framework presented in this paper, whether that is a useful choice for a threshold depends on T and C. It also depends on the benefits of the full set of T to society.

The simple framework presented in this paper suggests a future research agenda for ecological and environmental scientists. Shockingly, 35 years after the first Earth Day (Oriordan et al., 1995) scientists still have little data on how many environmental crises we are facing, and no sense of how many more will occur in the future. It should be a priority for scientists to compile large datasets that allow the estimation of T, r, and C for many sectors, and over time. Admittedly, the data available for the estimation of these parameters is often crude, but that does not excuse scientists from doing their best with the available data.

For environmentalists, this simple framework is also important. As the process of globalization increases, and economies become further connected, the rate of introduction of new technologies will undoubtedly increase in many sectors. Environmentalists need not view this as a threat, a reason for society to stop being innovative. Rather, it should be a challenge society must rise to meet. It will be our responsibility as environmentalists to make sure our capacity to prevent and deal with environmental problems grows in lock-step with the pace of technological innovation.

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