Estimating the Effects of Toxicants on Ecosystem Services

John Cairns, Jr.1,2 and B. R. Niederlehner1
1University Center for Environmental and Hazardous Materials Studies and 2Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061-0415 USA

Human societies rely on certain essential functions of ecosystems that have operated with no or minimal human intervention. These "ecosystem services" are essential to the quality of human life (1) and include the provision of food, the decomposition of sewage, the provision of potable water, and the replenishment of breathable air (Table 1). If these functions are no longer performed by ecosystems, they must be replaced through human engineering or people will suffer. Because of their anthropocentric importance, these attributes of ecosystems are a logical focus of environmental management. There may be some drawbacks to an exclusively anthropocentric view of protecting ecosystem attributes; some people believe there is an ethical and moral responsibility to also preserve attributes important to other animal and plant species. However, if an activity has the potential to damage environmental attributes that are of value to human society, data on the vulnerability of these ecosystem services will provide a persuasive basis for making necessary choices between environmental protection and other economic and social goals.

The Scale of Ecosystem Services

People most easily appreciate ecosystem services and environmental problems (threats to or failures in ecosystem services) that are intense, local, and immediate. An example of an ecosystem service on this scale is the cool shade of a tree on a hot, sunny day. Landscape architects estimate that a 70-foot shade tree can mitigate 900,000 BTUs of heat; this is worth 3 tons of air conditioning that costs about $19 a day in the United States at $0.072/kW-hr (2). In addition, the tree provides erosion control, air pollution mitigation, aesthetic satisfaction, habitat, and recreational value. An example of the same ecosystem service on a slightly larger scale would be trees around a parking lot in Tampa, Florida, on a 93°F (34°C) day. These trees could make the difference between returning to a car at 150°F (66°C) or one at 80°F (27°C) (2). Increasing the scale of the example still further, the 10–20°F differences in temperature between cities and surrounding rural areas in summer (3) are attributed to combinations of great areas of heat-holding pavement and the relative lack of open water and plants for cooling. Of course, the ecosystem service of microclimate control is readily appreciated on a personal level.

However, as an ecosystem service or environmental problem becomes less intense, more widely dispersed, and occurs chronically, its perception directly or personally is more difficult. In addition, cause-and-effect relationships become less obvious, more uncertain, and, therefore, less likely to motivate action. Low-intensity stresses that cause subtle rather than obvious damage, damage that is spotty or thinly dispersed over a wider area, and damage that will occur only over the long term are all less obvious threats to human quality of life, harder to quantify, and less likely to motivate a management response. For example, in contrast to microclimate control, the ecosystem service of microclimate control and the possible effects of a 2–8°F (1–4.5°C) temperature rise globally are not experienced directly, despite their cumulative and indirect importance.

Cumulative impact assessment recognizes that individually minor stresses can be significant when they are aggregated through time or space (4). As such, the scales on which various environmental problems are studied are not always sufficient to recognize cumulative environmental outcome (5,6). On the other hand, there are practical limits to the scale at which definitive and manipulative experiments on environmental problems can be conducted. Consequently, management decisions pertaining to problems affecting large areas or extended time frames must often be made on the basis of information that does not match the problem exactly in terms of stress intensity, time, and space. Extrapolations across scale are made to connect the responses that can practically be measured to the environmental effect of concern (7). This sets up a conflict. Only by expanding the scale of interest can the cumulative effects of human actions on ecosystem services be addressed. However, expanding the scale of interest depends on ecological models whose accuracy often cannot be definitively established (8).

Numerous functions of ecosystems are essential to the quality of human life, including the provision of food, the decomposition of sewage, the provision of potable water, and the replenishment of breathable air. Although attributes of ecosystems directly of use to human societies are not the only ones worth protecting, emphasizing their services may be the most effective means of communicating risks of toxicants to the general public. However, although spatial and temporal scales of experiments to assess risk vary relatively little, actual spatial scales vary considerably, from local environments to global ecosystems. Generally, models are used to bridge these gaps in scale. In this paper, we examine ways in which toxicity test endpoints have been developed to describe effects of pollutants on essential ecosystem functions and the ways in which results are then extrapolated to scales that risk managers can use. Key words: cumulative impact, ecosystem functions, integrated resource management, prediction, regional effects. Environ Health Perspect 102:936–939 (1994).

Address correspondence to J. Cairns, Jr., 1020 Derrin Hall, University Center for Environmental and Hazardous Materials Studies, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061-0415 USA. Received 2 February 1994; accepted 15 August 1994.
Table 1. An illustrative list of ecosystem services

| Capture of solar energy and later provision of food, building materials, biomass-based energy |
| Decomposition of wastes |
| Regeneration of nutrients (e.g., nitrogen fixation) |
| Storage, purification, and distribution of water |
| Generation and maintenance of agricultural soils |
| Pest control (e.g., insectivorous birds, bats) |
| A genetic library for development of new products (food, pharmaceuticals, and other beneficial chemicals) through both Mendelian genetics and bioengineering |
| Maintenance of breathable air |
| Microclimate control and macroclimate control |
| Ability to buffer changes and recover from natural stresses such as flood, fire, pestilence |
| Pollination of agricultural crops |
| Aesthetic satisfaction |

Table 2. Examples of stresses at various scales

| Scale | Example |
|-------|---------|
| Local | Heavy metal pollution |
|       | Oil spills |
| Landscape | Air pollution |
|          | Pesticides |
|          | Fertilizers/nutrients |
| Regional | Air pollution |
|          | Salinization |
| Continental | Acid rain |
|          | UV-B penetration |
| Global | Increases in atmospheric CO₂ |

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Table 3. Some examples of studies on toxic effects on ecosystem services at different spatial scales

| Toxicant                                                                 | Scale of Stress | Scale of Observation | Scale of Prediction | Study summary                                                                 |
|--------------------------------------------------------------------------|----------------|----------------------|---------------------|--------------------------------------------------------------------------------|
| Biomass production                                                       |                |                      |                     | Fly ash application reduces the yield of alfalfa (27).                      |
| Heavy metals                                                             | 1              | 1                    | 1                   | Rice yield increased when ambient CO₂ increased from 330 to 660 ppm (19).  |
| CO₂                                                                     | 1              | 1                    | —                   | A model for predicting rice yield based on dose–response data, mapping, and  |
| CO₂ UV-B                                                                 | 5              | 1                    | 5                   | simulation models for exposure (16).                                        |
| Acid rain                                                                | 4              | 2                    | 4                   | Linked geographic information on deposition rates, seasonal conditions, and  |
|                                                                         |                |                      |                     | natural buffering capacity to define regions most likely to be affected by  |
|                                                                         |                |                      |                     | acid rain. About 45% of the surface waters in eastern Canada are at risk (28).|
| O₃ air pollution                                                         | 2              | 2                    | —                   | Forest damage typical of ozone exposure examined using remote sensing; tying  |
|                                                                         |                |                      |                     | together information obtained on three spatial scales; controlled laboratory |
|                                                                         |                |                      |                     | toxicity tests, local surveys of foliar damage, and regional assessments     |
|                                                                         |                |                      |                     | through remote sensing (29).                                               |
| Decomposition of wastes                                                 |                |                      |                     | Total organic carbon removal by microbial communities from publicly owned    |
| Industrial waste                                                         | 1              | 1                    | 1                   | treatment works fell with the addition of toxic effluents (30).             |
| Regeneration of nutrients                                               |                |                      |                     | Forests responded to 3-year additions of nitrogen with increased net primary |
| NOₓ air pollution                                                       | 3              | 3                    | —                   | production. Soil organic matter acted as a sink for nitrogen additions. But  |
|                                                                         |                |                      |                     | following saturation there is increased leaching into aquatic systems (18). |
| Storage, purification, and distribution of water                        |                |                      |                     | Linked crop maps, recommended fertilizer application rates, aquifer and      |
| NO₃ fertilizer                                                          | 3              | 2                    | 3                   | susceptibility maps using a geographical information system. Predicted that 24%|
|                                                                         |                |                      |                     | of land area in Texas has a high potential for groundwater pollution from    |
|                                                                         |                |                      |                     | current agricultural practices (31).                                       |
| Generation and maintenance of agricultural soils                        |                |                      |                     | Common herbicides inhibit the breakdown of plant litter, yet accelerated      |
| Herbicides                                                              | 1              | 1                    | 1                   | nutrient losses (32).                                                       |
| Pest control                                                            |                |                      |                     | Cypermethrin applied to control lepidopteran forest pests also reduced the  |
| Pesticides                                                              | 2              | 2                    | —                   | reproductive success of a natural predator of the pest, the blue tit        |
|                                                                         |                |                      |                     | (Parus caeruleus) (32).                                                    |
| Genetic library                                                         |                |                      |                     | Linked regional chemical and biological effects models and predicted that 55,000|
| Acid rain                                                               | 3              | 1                    | 3                   | lakes in eastern Canada had lost at least 20% of their biotic diversity (34).|
| Maintenance of breathable air and climate control                       |                |                      |                     | Nitrogen additions decreased the methane consumption of forest soils (39).   |
| NOₓ air pollution                                                       | 2              | 2                    | —                   | Forests affected by smelter pollution took longer to recovery from natural    |
|                                                                         |                |                      |                     | fire disturbances (36).                                                    |
| Ability to buffer changes and recover from stress                      |                |                      |                     |                                                                           |
| Smelter pollution                                                       | 2              | 2                    | —                   |                                                                           |

Spatial scale is ranked from 1 to 5: 1 = local; 2 = landscape; 3 = regional; 4 = continental; 5 = global. When no explicit extrapolation was made, no scale is assigned (—).
conditions for species that have no demonstrable utilitarian purpose but that may have aesthetic and social value.

Summary

Risk assessment procedures that incorporate information on the effects of toxicants on ecosystem services are likely to provide a persuasive basis for making environmental decisions. Although attributes of ecosystems directly of use to human societies may not be the only ones worth protecting, focusing on them may be the most effective means of communicating risks to the general public and may prove to be closely associated with other attributes whose value is recognized by a smaller segment of society. While toxicity tests with ecosystem services related to agriculture, fishery, and forestry industries are common, toxicity tests related to other ecosystem services are less developed, as are methods for extrapolating to regional and global spatial scales. In addition, while there is an inescapable conflict between the desire to have evidence that is reliable and the desire to have evidence that is relevant, management can proceed with calculated uncertainty.

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