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# Stress, Environmental

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## Glossary

**Acute** An exposure to an environmental stress that is brief in relation to the temporal scale of the biological system exposed.

**Biosphere** All the plants and animals on Earth, together with the habitat they need for long-term survival.

**Biotic impoverishment** The decline of a species to the point of having little or no ecological significance.

**Chronic** An exposure to an environmental stress that is comparable in duration to the temporal scale of the biological system exposed.

**Ecosystem services** The structures and functions of natural biological systems which directly or indirectly support human life.

**Environmental stress** An action, agent, or condition that impairs the structure or function of a biological system.

**Function** The performance of a biological system as a rate.

**Structure** The number, kinds, and arrangement of component parts at one point in time.

**Tipping point** When a complex system goes into disequilibrium and is replaced by a new system in evolutionary time.

**Uncertainty** Imperfect knowledge concerning the current or future state of a system under consideration; a component of risk resulting from imperfect knowledge of the degree of hazard or of its spatial and temporal pattern of expression.

## What is Environmental Stress?

Three components are involved in the relationship that defines environmental stress. First, there is the environmental stress itself as defined previously. However, the environmental stress can only be defined in reference to its interaction with some biological system. Therefore, there must be a receptor – a biological system that is exposed to the environmental stress. Finally, there must be an adverse response – a particular structure or function of the receptor that is changed by exposure to the environmental stress to the detriment of that system. If the survival of that biological system (or another) is not threatened by the change, then there is no environmental stress.

## Types of Environmental Stress

### Natural versus Anthropogenic

Environmental stress can be either natural or anthropogenic (i.e., resulting from human actions) in origin. Many enironmental stresses, such as most hurricanes, droughts, floods, and fires are a periodic feature of life on Earth. In contrast, environmental stresses such as the production and release of new chemical compounds and large-scale land-use changes result directly from human actions. Ironically, the suppression of natural environmental stresses such as fires and floods can also be a source of stress to biological systems resulting from human actions. Some species have adapted to periodic disturbance and cannot continue without them. For example, some seeds will germinate only after exposure to the high temperatures of a fire. However, such adaptations take time to evolve. Other stresses, such as the meteor that probably wiped out 70% of earth's species 65 million years ago, occur too quickly and intensely to result in adaptation.

Natural and anthropogenic stresses often have common components. For example, both hurricanes and wood harvesting result in downed trees. However, as a result of recent major increases in human population, technological capabilities, and standard of living globally, the amount of anthropogenic environmental stress has increased greatly. Anthropogenic environmental stress existed even 50,000 years ago, when fires set to aid hunters are thought to have altered the landscape in central Australia (Flannery, 1999). Since that time, human population increased slowly to 1 billion people in 1804 and then rapidly to 6 billion people in 1999, and the population is expected to increase by another 1 billion people every 12–15 years. The cumulative environmental stresses resulting from these exponential increases in human population are exacerbated by technologies that expand the character and scope of changes humans can make to their environments. Both the agricultural revolution (about 10,000 years ago) and the industrial revolution (about 200 years ago) expanded the types of anthropogenic stresses on the environment. In addition, increased affluence for people throughout the world increases the environmental stress on natural systems by increasing the per capita human use of natural systems. Humankind's collective ecological footprint (i.e., the amount of earth's surface required to produce the resources used and to assimilate the wastes produced) is rapidly increasing (Rees, 1996) at the same time that productive land is decreasing through erosion, salinizetion, and unsustainable land-use changes. The ecological footprint for an average person can range from 0.4 ha required to provide for the lifestyle of one person in India, where the level of affluence is quite modest, to 5.1 ha for a person in the US. If the lifestyle of every person living in 1996 was elevated to that of a typical North American, an additional two earths would be needed to provide the surface area required (Rees, 1996).

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## Characterization of Environmental Stress

Environmental stresses of both natural and anthropogenic origin can be characterized on the basis of their spatial distribution, temporal distribution, intensity, and novelty (Kelly and Harwell, 1989). Spatial distribution of a stress describes its geographic extent and pattern. One basic concern is the size of the area affected by the stress, i.e., is the stress local, regional, or global in extent? Some kinds of environmental stress have an intrinsic spatial scale: A poorly dispersed chemical spill may be quite local in its effects, whereas air pollution can affect entire regions. Some stresses will be consistently spread over an area, whereas others will occur irregularly in patches. Cumulative environmental stresses, in which many individual small patches can join together to have larger impacts at a larger scale, have been documented. In one example at the local level, the cumulative loss of small wetland areas within a watershed had demonstrable adverse effects on water quality (Johnston et al., 1988). The magnitude of the biological responses to a stress will often be modified by the spatial distribution of environmental stress, for example, whether key features in the environment such as riverbanks or fencerows are affected or whether similar habitat patches nearby are left unaffected. The field of landscape ecology deals with these factors.

The temporal distribution of a stress describes its frequency and duration. Some stresses, such as chemical spills, are one-time occurrences. Others, such as the winter season or wildfires, can be expected to reoccur either at predictable or at unpredictable intervals. Some stresses rapidly ameliorate; others remain for long periods of time. The terms ‘‘acute’’ and ‘‘chronic’’ are used to describe the duration of a stress. Acute refers to stresses of short duration, whereas chronic refers to stresses that last longer in relationship to the duration of the biological system they affect. In some cases, the timing of the stress in relationship to other biological events may modify the magnitude of the biological response. For example, the spawning season for amphibians in northern North America in spring corresponds to the greatest thinning of the ozone layer and ultraviolet (UV) light penetrations. The developing eggs of some of these species have been shown to be affected adversely by UV light (Blaustein and Wake, 1995). This temporal factor may be contributing to observed declines in the numbers and kinds of some amphibian species present in those areas.

The intensity of an environmental stress describes its relative ability to evoke a response from the receptor. With increasing intensity, the impact may progress from a few, slightly affected, particularly sensitive components of the biological system to most components being grossly affected. Small changes in the histology or physiological state of individual species can be expected to occur at lower stress intensity and chronologically before changes in survival at a similar temporal and spatial scale. Similarly, at the community level, changes in species composition can be expected to occur at lower stress intensity and chronologically before changes in the community functions. The intensity of hurricanes is routinely ranked from category 1 to category 5. In the case of chemical pollution, the intensity of the environmental stress can be described by the concentration of the chemical in the environment. Thus, copper is a natural, background constituent of water in a river or stream. Intake of copper is essential for both animal and plant life. However, concentrations higher than 10 μg l$^{-0}$ in river water can be expected to eliminate a few sensitive species and change the age class distributions in others by changing reproductive success. Higher concentrations can be expected to affect more components in more obvious ways. For example, in Shayler Run, Ohio, 120 mg l_1 of copper caused fish kills at some times of the year, avoidance of the stream reach by other fish, declines in macroinvertebrate community species richness, and other gross responses (Geckler et al., 1976).

The novelty of an environmental stress will determine whether or not biological systems will have mechanisms in place to deal with it. Environmental stresses that resemble naturally occurring stresses in their mode of action will be dealt with by the system in the same ways. Novel stresses may be more devastating because no mechanisms have evolved to cope with them. For example, when human harvests of wood products mimic relatively frequent natural events such as treefall or windthrow in their spatial extent, mechanisms are in place in the biological system to recover from this event. When human-created gaps are larger and more intense than the historical disturbances, these same mechanisms may not help. Similarly, some natural systems can break down, render biologically unavailable, or disperse low levels of some chemical materials that are naturally occurring or that resemble naturally occurring substances without detectable disruption. The ability of a natural system to receive materials at some concentration, including anthropogenic wastes, without being degraded is its assimilative capacity. However, overloading a system with too much waste destroys both the structure and function of the ecosystem and its future assimilative capacity.

## Receptors and Responses

An action, agent, or condition can be a stress to one biological system whereas simultaneously not affecting many others. Because environmental stress is defined by the observation of an impaired biological system, the probability of identifying an environmental stress is related to how thorough the search for impairment has been. Although there are an almost unlimited number of receptors and responses that could be affected by any particular environmental stress, it is generally impractical to monitor more than a small sample. Also, experience has shown that it is easy to overlook a response that may be important. For example, DDT caused eggshell thinning in some birds, although routine toxicity tests failed to identify this response.

The most useful responses to examine for studies that aim to influence decisions about environmental management tend to be those that are clearly related to stated environmental goals. These tend to be responses that are both biologically and socially relevant and that can be measured reliably. Sometimes, the responses that society cares most about cannot be measured directly. Other, presumably related, responses can be measured. In addition, responses that occur earlier in a chain of events, and which lead to an ecologically relevant

**Table 1** Examples of receptors and responses used in studies of environmental stress

| *Level of biological organization* | *Structural responses* | *Structural responses* |
|---|---|---|
| Individual | Condition | Growth |
| | Fat stores | Fecundity |
| | Histopathology | Physiological function |
| Population | Occurrence | Yield |
| | Abundance | Gross morbidity |
| | Age structure | |
| Community | Species richness | Production |
| | Trophic structure | Respiration |
| | Proportion of exotics | Extinction rate |
| Ecosystem | Nutrient pool size | Materials cycling |
| | Biomass | Materials export |
| Landscape | Habitat proportions | Regional production |
| | Patch size | Materials export |
| | Perimeter-to-area ratio | Resistance to stress |

event, may be useful as early warnings of conditions that have the potential to cause unacceptable damages. **Table 1** summarizes some responses that have been used to evaluate environmental stress and guide environmental management. As the goals in environmental protection have changed over time, so have the responses that are monitored. Most early tests of environmental stress were designed to protect one species – humans. This objective spurred tests that monitored the physiology of species used as human surrogates. Gradually this protection was extended, first to domasticated animals and plants and then to commercially valuable wild species. These additional tests monitored the survival of populations of important species. Currently, goals extend beyond the protection of individual species and include the protection of biodiversity and ecosystem services (i.e., those structures and functions of natural biological systems that directly or indirectly support human life). Assessments should reflect these new goals because millions of species in the environment must be protected. Each species cannot be examined individually. In practice, a few species must serve as surrogates for many others, and a few systems serve as surrogates for many others.

Environmental responses may be characterized by type and scale. Responses are either structural (e.g., describing the number and kinds of components, such as the macroinvertebrate community structure) or functional (e.g., describing performance or flux, such as biological oxygen demand or primary production). Also, unique responses may occur at many distinct spatial and temporal scales and levels of biological organization (e.g., cells, tissues, organs, organisms, populations, communities, ecosystems, landscapes, biomes, and the world). Some attributes at higher levels of biological organization are not present at lower levels; for example, energy flow and nutrient spiraling are properties of ecosystems but not of organisms. Other attributes are present in some form at many levels; for example, one can measure the diversityof phenotypes at the population level and the diversity of species at the community level. Environmental goals can be stated on many of these levels, but tests of environmental stress are largely limited to those levels that are more accessible to human observation.

An awareness of scale provides two contrasting approaches to study environmental stress. Top-down methods start with observed damage to a biological system of interest and investigations move down through hierarchical levels. Component structures and functions are examined in order to diagnose the causative agent and plan remedial actions. At the outset, the damage has already been done, so the relevance of the changes is known. However, the causative agent and the chain of events leading to unacceptable damage are not known. Bottom-up methods start with an environmental stress, and the effects of that stress on biological systems are determined through designed experiments. Because experiments on small and quick biological systems at lower scales are generally less expensive, these experiments are most common. In bottom-up assessments, the causative agent is known at the outset, but the importance of ultimate changes at any ecologically relevant higher scale is not known.

Microcosms and mesocosms are attempts to increase the spatial and temporal scales and level of complexity in biological systems that can be used in designed experiments of environmental stress. Microcosms and mesocosms simulate important attributes of natural systems in laboratory or outdoor conditions. As the names indicate, the main difference is in size. Microcosms are sometimes small enough to hold in one's hand; mesocosms may cover one acre. Neither is an exact reproduction of any real ecosystem, but they do enable studies of environmental stress in ways that avoid damaging natural systems. On rare occasions, environmental stress may be studied in designed experiments using entire ecosystems. For example, one whole system manipulation was carried out in the Hubbard Brook drainage basin in New York State (Bormann and Likens, 1979). Such efforts are of great value in calibrating models.

## A General Environmental Stress Syndrome

A threshold is defined in *Webster's Third International Dictionary* as ''the point at which a physiological or psychological effect begins to be produced.'' Moving upwards in biological systems, this effect can be generalized to the point at which a response begins to be produced. Woodwell (1974) asked the question

> Is it reasonable to assume that thresholds for effects of disturbance exist in natural ecosystems or are all disturbances effective, cumulative, and detrimental to the normal functioning of natural ecosystems?

Thresholds may be artifacts of testing procedures, reflecting the power of particular test designs rather than a feature of the system being studied. However, perhaps the more important question is ''Can humans detect those environmental changes that are important to their own quality of life?'' As is the case with human health, the gradient in environMental systems may be extensive between robust health and collapse in some cases, but an abrupt transition from health to collapse may occur in others. By reviewing information available about the behavior of ecosystems under stress,

**Table 2** Responses expected in stressed ecosystems

| *Energetics* |
|---|
| Community respiration increases |
| Gross production/community respiration (*P*/*R*) becomes unbalanced |
| Maintenance cost increase; gross production/standing crop biomass (*P*/*B*) and community respiration/standing crop biomass (*R*/*B*) ratios increase |
| Importance of auxiliary energy increases |
| Exported or unused primary production increases |
| Nutrient cycling |
| Nutrient turnover increases |
| Horizontal transport increases, vertical cycling of nutrients decreases |
| Nutrient loss increases |
| Community structure |
| Proportion of *r*-strategist increases |
| Size of organisms decreases |
| Life spans of organisms or parts decrease |
| Food chains shorten |
| Species diversity decreases, dominance increases, redundance declines |
| General system-level trends |
| Ecosystems become more open |
| Autogenic successional trends reverse |
| Efficiency of resource use decreases |
| Parasitism increases, mutualism decreases |
| Functional properties more robust than structural properties |

Source: Reproduced from Odum EP (1985) Trends expected in stressed ecosystems. *Bio Science* 35: 419–422, with permission from Jstor.

several researchers have tried to outline general ways in which ecosystems respond to various types of stress (Barrett et al., 1976; Odum, 1985; Rapport et al., 1985; Schindler, 1990). An environmental general stress syndrome at the ecosystem level may include the features listed in Table 2; however, experience is continually modifying this list. These efforts to derive an environmental stress syndrome are important because they define a progression of impact in which some minor changes precede other more serious ones. By recognizing changes early in the progression of impact, remediation could begin and crises could be averted. However, the challenge of finding one general description for widely varying systems, challenged by widely varying combinations of stress, is daunting.

Stressed ecosystems often recover once the stress has been removed. However, sometimes human assistance is required, and this process is called ecological restoration or rehabilitation. Restoration has as its goal the return of an ecosystem to a close approximation of its condition prior to the stress and the recreation of a functioning, self-regulating system that is integrated into the ecological landscape in which it occurs. The practice of ecological restoration often involves the reconstruction of physical conditions present prior to the stress, chemical cleanup, and biological manipulation, including revegetation and the reintroduction of native species.

## Stress Assessments

Studies of environmental stress can have different purposes. In some studies, the purpose is accounting, i.e., what is the existing condition of this biological system? This question can be important for the purposes of disclosure, national environmental accounting, prioritization, and remediation. Studies of environmental stress can also be used for prediction, i.e., will this action cause a problem or which action is better? Predictive studies are used to register chemicals, rank risks, design processes, etc. Another distinct purpose for studies of environmental stress is to provide early warning of conditions that, if left unchecked, will result in significant damage to human quality of life. By detecting damage before it is of a magnitude that is unacceptable, crises can be averted.

### Appraisal

Studies of environmental stress can assess the condition of biological systems that exist at a particular point in time. When repeated over time, trends in condition can be assessed. Appraising the condition of a biological system can confirm that environmental quality is adequate or can serve to define an existing environmental problem. Many countries are undertaking a national accounting of the health of their ecological systems. For example, the Canadian State of the Environment Reports and the Environmental Monitoring and Assessment Program in the US measure the condition of rivers, lakes, forests, wetlands, arid lands, and agroecosystems. Although some of these programs measure common sources of environmental stress, as well as biological response, others focus solely on response. Once a problem is found, additional studies to diagnose the problem would include measures of environmental stress.

### Prediction

Often, the easiest way to maintain environmental quality is to prevent damage before it occurs. This strategy requires prediction of the future. Such predictions can come from observations of the effects of similar stress on similar systems or from extrapolations or models from the effects of dissimilar stresses or the effects on dissimilar systems.

The ability to extrapolate the measured effects of environMental stress at one level to consequences at a higher hierArchical level depends on the use of mechanistic models that describe the interaction of component parts. The model is then calibrated, i.e., compared to observed behavior of a system under environmental stress and adjusted to maximize the accuracy of its predictions. Currently, there are a few calibrated models for large-scale predictions. Also, it is unlikely that calibrated models will be available for some processes because their spatial and temporal scales make testing impractical or unethical. All hypotheses and theories are more readily accepted if they have withstood rigorous testing. Predictions of environmental stress are no exception. As a general rule, multiple lines of evidence published in peer-reviewed profissional journals whose contents have been reviewed by respected professionals result in acceptance both by the person carrying out research on environmental stress and by mainstream science. Generally, validation occurs in two primary ways: (1) a designed test of a hypothesis derived from a theory, especially by those having nothing to do with its development, and (2) consilience with other well-accepted and tested theories. Predictions of environmental stress are particularly likely to be challenged outside the scientific community because taking precautionary measures to avoid conditions estimated to cause stress often requires changing societal and industrial practices and sometimes engenders costs. Environmental stress associated with global warming is a good illustrative example. Limiting greenhouse gases in the atmosphere will affect the lives of almost every person on the planet, as would significant global warming. In this case, the entire planet is the experimental unit, making designed tests of impact at the same hierarchical level as that of the environmental problem impossible since there is no control planet available. As a consequence, much uncertainty about the probable effect of increased greenhouse gases will persist. However, management decisions about such gases must be made and must be based on the best available information; managers must act even though there is uncertainty accompanying any estimate of risk. Fortunately, most forms of environmental stress, such as exposure to potential toxicants, are much more easily validated.

## Early Warning

Monitoring is a systematic and orderly gathering of data to ensure that previously established quality control conditions are being met. Biomonitoring applies this activity to the detection of environmental stress. In this case, the goal is to provide an early warning that unacceptable levels of environmental stress have occurred. As is the case in an intensive care room in a hospital when heart and respiration rates are monitored and unacceptable conditions are detected, an immediate action is mandatory. In any form of quality control, the more rapidly the information becomes available, the more quickly corrective action can be taken. Extensive use of information technology has made complete automation of some monitoring systems, including triggering the remedial action, possible. However, in the absence of carefully selected goals and objectives related to the decisions to be made, it can also generate huge amounts of unnecessary and inappropriate data.

Setting the corrective action threshold low to ensure early detection of deleterious change seems prudent, but it can also produce false-positive readings. A false positive is an indication that some deleterious effect has occurred when in fact none has occurred. Emergency team response to eliminate stress can be quite expensive and unpopular with management. False positives are usually most numerous when monitoring is in the early developmental stages and decrease substantially as experience is gained. Avoiding false positives by setting the action threshold well beyond the response threshold will probably result in false negatives. A false negative is information that no deleterious effects have occurred when in fact some have occurred. Thus, ecosystem damage occurs because no corrective action alert is produced. These false signals are clearly a matter of prime importance in the design of all monitoring systems. The dilemma is that one wishes to detect environmental stress at the earliest possible moment, but this may result in false signals since sensitive end points are often highly variable.

## The Biospheric Life Support System

Earth is now in its sixth biosphere. This sixth biosphere provides unique conditions in which the genus Homo, including Homo sapiens, evolved and flourished. The biosphere also provides the resources on which the human economy is based. In terms of biospheric function, a species must not only be present but present in sufficient numbers to be effective ecologically. The present biosphere has already suffered from a substantial loss of species due to both extinction and biotic impoverishment. The tipping point for the present biosphere is unknown. Changes caused by passing a tipping point are irreversible; consequently, prudence dictates avoiding such a tipping point.

## Future Trends

In view of unprecedented growth in human population and the desire to raise the standard of living above the subsistence level for most of the world’s people, there are new challenges for those studying environmental stress. The level of environmental stress from food production and energy usage may increase. Simultaneously, there is a great pressure to increase food production to feed the increasing human population, and the need to protect intact biological systems and ensure their robust functioning so that they can continue to provide necessary ecosystem services will become more pressing. Some approaches to these problems are of great interest.

The World Commission on Environment and Develop-Ment (1987) of the US published Our Common Future, which focuses attention on the future condition of the planet, arguably more so than any publication that preceded it. The commission defined sustainable development as

> development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

This presents a curious combination of words because ‘‘sustain’’ means to continue and ‘‘development’’ is usually associated with growth. However, infinite growth on a finite planet is clearly not possible.

In December 1989, the General Assembly of the United Nations (UN) attempted to address the problems identified in Our Common Future (World Commission on Environment and Development, 1987) by organizing the UN Conference on Environment and Development (popularly known as the Earth Summit), which was held in Rio de Janeiro in June 1992. This conference resulted in a heightened awareness of the interrelatedness of environmental degradation and stress, population development, and depletion of natural resources. Previously, all had been viewed as separate problems, but now attempts are being made to address them as an interactive system. The resulting Rio Declaration on Environment and Development endorsed the following principles: (1) Nations should not cause damage to the environment of other states and areas beyond their borders; (2) eradicating poverty and reducing disparities in worldwide standards of living are indispensable requirements for sustainable development; (3)

the polluter, in principle, should pay the cost of pollution; (4) states should discourage or prevent trans-boundary movements of activities and the substances that endanger health or environment; and (5) scientific uncertainty should not be a reason for postponing urgent measures to prevent environmental degradation.

Sustainable use of the planet will not be possible if ex-Cessive environmental stress impairs the ecological life support system that provides necessary ecosystem services. As a consequence, keeping environmental stress at tolerable levels has a direct bearing on the quality of life for humans. Events beyond human control, such as a large extraterrestrial object striking earth, make it impossible to guarantee that reducing environmental stress will ensure sustainability.

The theory of ''weak sustainability'' asserts that human society is sustainable provided that the aggregate stock of manufactured and natural assets is not decreasing. Thus, the loss of the whaling industry would not impair sustainability if the proceeds of liquidation are invested in industries of comparable income-producing potential. Pearce and Atkinson (1993) dispute the assumption that natural and human-made capital are sustainable in this context. They assert that strong sustainability requires that natural capital stocks be held constant, independently of the human-made capital. A weak sustainability scenario would permit considerably more environmental stress than a strong sustainability scenario. Conventional monetary analyses are biased against strong sustainability. For example, at a discount rate of 5%, the current value of ecological services for an American life span (about 76 years) from the present on is approximately 2.5 ¢. Using this approach, the farther into the future one projects, the less valuable natural systems appear, thus diminishing the significance of environmental stress.

Reducing environmental stress requires the cooperation of the entire society. One of the most important components is the industrial system. Fortunately, the field of industrial ecology (IE) is developing worldwide (Hawken, 1993). The goal of IE is to reduce environmental stress at all stages: (1) extraction of raw materials, (2) processing, (3) disposal of manufacturing wastes, (4) packaging, and (5) reincorporation into the environment at the end of the product's life in a nonstressful way, ideally in a way that enhances ecological integrity. IE's primary goals are to (1) reuse materials as much as possible, (2) reduce energy consumption per unit produced, and (3) design both processes and products so that they can be reincorporated into the environment with minimal stress. Books such as *Engineering within Ecological Constraints* (Schulze, 1996), which was produced by the National Academy of Engineering, are directed toward achieving this goal.

*See also:* Adaptation. Biodiversity, Origin of. Carrying Capacity, Concept of. Ecosystem, Concept of. Energy Use, Human. Extinction in the Fossil Record. Functional Diversity. Global Species Richness. Population Dynamics

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