Module 2

Biocomplexity in the North

Developed by Lawrence K. Duffy, Associate Dean, Graduate Projects and Outreach, College of Science, Engineering and Mathematics, and Professor, Chemistry and Biochemistry Department, University of Alaska Fairbanks; and Stan Wright, Executive Assistant, Alaska Basic Neuroscience Projects, Institute of Arctic Biology, University of Alaska Fairbanks

Key Terms and Concepts

- biome
- biocomplex systems
- bioindicator
- boomerang paradigm
- carrying capacity
- causation
- chemical cycles
- dissolution
- ecosystem
- ecosystem services
- emergent property
- energy flow
- environmental robustness
- equilibrium
- food chain
- food chain efficiency
- food web
- Gaia hypothesis
- growth
- homeostasis
- natural capital
- negative feedback

- niche
- over-exploration
- positive feedback
- precautionary principle
- reorganization
- resilience
- social irritation
- stability domain
- synergism
- values
- world view

Learning Objectives/Outcomes

Upon completion of this module, you should be able to

1. explain the significance of positive and negative feedback.
2. give examples of using positive feedback to make desired changes.
3. identify how emergent properties arise from hierarchical organization of systems.
4. describe complex environmental system cycles in terms of material and energy cycling.
5. illustrate the effect of human-induced changes on ecosystem services.
6. identify bioindicators and biomarkers of human and ecological health.

Overview

Life on Earth is supported by the natural cycling of chemical elements. The availability and interaction of these elements at multiple scales has both direct and indirect influences on individual organisms and environmental systems. Living systems also depend on energy flow.

Understanding the sources, sinks, transformations, and feedbacks of these essential elements and energy is a critical step in determining their behaviour under specific environmental conditions. The consequences of human perturbations on essential nutrient cycles in soils, sediments, and other systems must be recognized.

A major challenge is to understand how the environmental services are being affected by human activities, including agriculture, development, energy production, and energy use. It is important to understand the impact of these changes at multiple scales and to determine whether the harm to ecosystems can be reduced through modification of human behaviour and application of relevant technologies.

One of the keys to understanding, maintaining, and improving environmental *robustness*, *health*, and *well-being* is to strengthen the links and interaction among scientific knowledge, engineering know-how, and social benefit.

Environmental *robustness* refers to the functional soundness of environmental systems, from local to global scales. Important aspects of robustness include a system’s ability to resist outside stress and its capacity to adapt, develop, regenerate, and evolve.

Environmental *health* focuses on the interrelation between human health and the health of other species in a healthy ecosystem. Contaminated water and air, endocrine disrupters, and even biological terrorism pose important research challenges in a world in which human systems have become agents of change that effect rural and natural landscapes, including the movement of organisms and materials in air and water.

Environmental *well-being* refers to the ability of the environment to support all life, including human economic and social systems. The efficiency and sustainability of environmental services, the cycling of materials, the flow of energy, and the maintenance of organismal balance and diversity are all important priorities.

Lecture

Feedback Systems

Human interaction with its surroundings can be viewed as an interaction between the human social system and the ecosystem. An ecosystem is everything in a specified area—air, water, soil, and living organisms. The living organisms, including micro-organisms, are the biological community. The ecosystem provides services to the human social system by transferring materials and energy to the social system. An example of this interaction between ecosystem and social system is the decline of marine mammals in Alaska and the growth of commercial fishing. It has been proposed that the decline of seals, such as the Steller sea lion, and other fish-eating animals is related to a reduced fish supply because of heavy fishing, especially non-targeted bycatch species. In turn, killer whales that previously preyed on seals, have switched to sea otters, thereby reducing the sea otter populations in the Aleutian Islands. Sea urchins are increasing because of reduced sea otter predation, and since sea urchins eat kelp, the kelp forests are decreasing. Unintended consequences, such as the loss of sea otters and kelp forests, are not unusual any more in the North. This is an example of feedback at work.

Positive and negative feedback are powerful forces that shape the behaviour of both social systems and ecosystems. Negative feedback provides stability, while positive feedback can be seen in exponential population growth when there is a surplus of food or living space. Positive feedback increases change. Even if a change is downward, positive feedback can make the downward change occur faster, as in the case of the sea otter. Often, positive feedback causes one plant or animal to replace another.

Negative feedback is a circular chain of effects that opposes change. As a component of the cell, tissue, or ecosystem, changes from the normal cause other components of the system to also change in order to reverse the original change. The function of negative feedback is to provide a source of stability by keeping the components of the system within limits. Homeostasis in an organism's biochemistry is an example of negative feedback. Population regulation is also an example of negative feedback in which the feedback from food and resource ability set the population limit. *Carrying capacity* is the population that the food supply will support on a long-term sustainable basis. In a closed system, because the resources such as food and space are limited, no population can exceed the carrying capacity of its environment for long.

Scientists have measured changes in many populations over the years. When births exceed deaths, the population grows. However, this reduces food; so, eventually, deaths can exceed births. The exponential growth in the first part of the feedback loop is followed by population regulation in the next part.

Negative feedback leads to a fluctuation in population size around the carrying capacity. This fluctuation occurs because

- negative feedback is not precise
- other factors, such as contaminants, can have an impact on births

The significance of positive and negative feedback systems is that they can interact, creating a complex system. Ecosystems and human social systems have many positive and negative feedback loops. The development of biological systems and social systems is based on a complex interplay of positive and negative feedback, called biocomplexity. Because of biocomplexity, ecosystems and social systems function best when there is an appropriate balance between forces that promote change and the forces that provide stability. Ecosystems and social systems have a tension between forces that resist change (negative feedback) and forces that promote change (positive feedback). Based on the situation, negative feedback may dominate sometimes, and positive feedback may dominate at other times. Ecosystems and social systems may stay more or less the same for long periods of time because of negative feedback; but positive feedback can lead to change and even cause a sudden switch or shift of regime.

Student Activity

1. Name an example in or near your community of an interaction between an ecosystem and a social system.
2. What are the feedbacks as a result of this transfer?

Biocomplex Adaptive Systems and Emergent Properties

Because biological and environmental systems have many components and interactions between components (feedback), they have the ability to change and adapt to new conditions. As complex adaptive systems, biocomplex systems generate new properties called emergent properties. These emergent properties are the distinctive features and behaviours that arise from the adaptivity and organization of the complex system. The emergent properties of biocomplexity include self-organization, stability domains, and complex cycles. (See table 2.1.)

Table 2.1 Levels of biological organization and their characteristic structural and functional attributes

Individual	One whole organism. Individuals have size, shape, health, or condition. They grow, reproduce, and die over time.
Population	A group of individuals of the same species occupying the same area at a given time. Populations have abundance, biomass, size, and age class structures. They compete, exploit prey, and produce biomass.
Assemblage	A set of coexisting populations defined by phylogeny, location, or lifestyle. Assemblages are intermediate to populations and communities and have some of the properties of both groups, depending on how they are defined.
Community	The collection of all organisms that live in a specific region at a given time. Communities have biomass, diversity, evenness, richness, and trophic structure. They produce biomass, process materials, and change through succession over time.
Ecosystem	All of the organisms in an area, together with the physical environment with which they interact. Ecosystems have biological as well as physical and chemical structure. They move energy, materials, and nutrients.

In living systems, there is a hierarchy of organization that grows from molecules and cells, to individual organisms, to populations, to ecosystems (see fig. 2.1). Each level has a characteristic behaviour different from the previous level. These hierarchical distinct behaviours—called emergent properties—work to give that level a property of its own that is greater than the sum of its parts. At the molecular level, an effect that is greater than the sum of the individual effects is called synergism. At higher organizational levels, because the parts are interconnected and their behaviour is shaped by feedback loops, survival responses to environmental change can occur. As biocomplexity increases, so also does the richness of expression of emergent properties. Neuroscientists believe emotions, such as fear and love, are emergent properties. Social organization is an example of an emergent property at the population level.

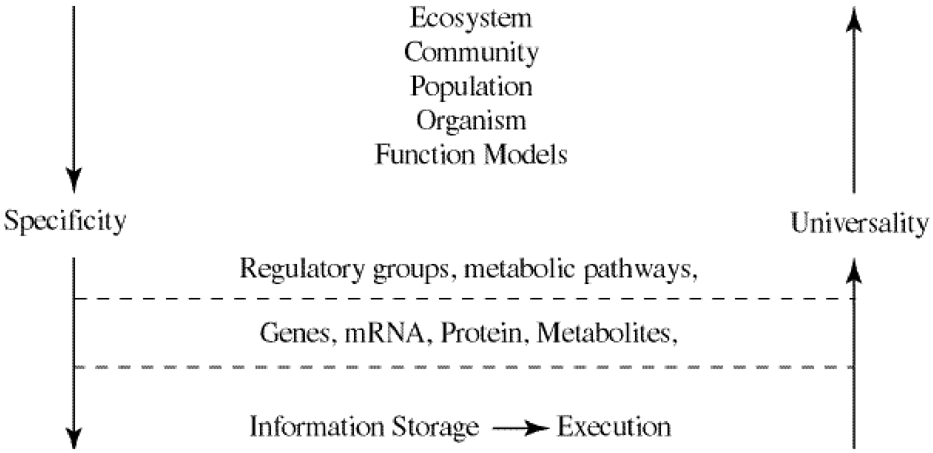

Fig. 2.1 Biocomplexity pyramid (adapted from Oltai and Barabasi)

The components of ecosystems are limited by their connections to the other parts, so the carrying capacities for all species together are an emergent ecosystem property. The food supply for each species depends on the biological production and on the food web channels between prey and predator. Ecosystems organize themselves by means of an assembly process similar to the natural selection of biological evolution. Assembly in this context means “fitting the parts together” into a biological community. This community assembly process—a biological self-organization—is an emergent property of ecosystems.

Gerald Marten, in *Human Ecology* (2001), points out several rules of survival in community assembly for a newly arriving species:

- adapted to the physical conditions at the site
- can survive throughout the year
- site has the right food
- can grow and reproduce at the site
- have the ability to avoid being preyed on too much

Community assemblies are made up of niches. An ecological niche defines a species’ role in the food web. Food webs are emergent properties of ecosystems. The ability to change or switch is also an emergent property of all complex adaptive systems, such as ecosystems and social systems. Organisms stay in stability domains related to their niche but can be moved to a new stability domain; that is, they can switch because of an external disturbance.

A progressive change owing to self-organizing assembly, and a sudden change owing to stability domain switching, combine to form a complex system cycle. The cycle can be characterized by four components:

- growth
- equilibrium
- dissolution
- reorganization

Growth is a period of positive feedback and self-organizing assembly leading to expansion and increasing complexity. *Equilibrium* is the period of stability with a high level of connection between its parts and dominated by negative feedback loops. *Dissolution* occurs when the system is destroyed by an external disturbance that creates dramatic change via positive feedback loops; the system then moves from its current stability domain to a new one. The system has the possibility of moving into a variety of new stability domains. *Reorganization* occurs when the system begins to reorganize around one of these new stability domains. Chance and outside factors can be important to the course initiated during reorganization. Complex system cycles in ecosystems can be described as ecological succession. In social system cycles, policies can dramatically change, thus reflecting and affecting the cycle. Policies are usually well developed during equilibrium but are rejected as inadequate during dissolution. New policies and frameworks are formulated during reorganization. An effective society has the ability to function during all four stages of the complex system cycle.

People living in the Arctic face many challenges posed by economic circumstances; lifestyle; exposure to contaminants and severe cold; dietary changes; as well as geographic and political isolation. Indigenous peoples, with their continuing ties to the land and traditional food (and often with marginalized status) are generally the most affected by these challenges. In its report, the Arctic Monitoring and Assessment Program (AMAP) highlighted the risks posed to human health and wildlife by persistent organic pollutants (POPs), heavy metals, and long-lived radionuclides. Since we all depend on the ecosystems for food and natural resources, the risk of the contaminants damaging ecosystems calls for a precautionary approach.

Ecosystems renew their resources by processing the waste so that it can be used again by parts of the system. The handling of waste and the cycling of material to renew natural resources are considered ecosystem services.

Over-exploration can switch an ecosystem to a new stability domain. To strive for sustainable management in a complex system, we need to be aware of the key aspects of uncertainty:

- sources of threats of harm
- effects of threats of harm
- validity of cause-and-effect relationships

The limited capacity of environmental science to provide fast answers and reliable predictions can make environmental management a political issue. The "precautionary principle" has been developed, particularly in Europe, to guide regulation of human activities that have serious unpredictable risks. However, its application can be controversial when the activity provides major social or economic benefits. The global community has accepted the basic tenant of precaution—that evidence of high risk need not be completely understood to justify mitigating action—and the principle is codified by many recent international agreements, such as the Stockholm Convention. International law increasingly acknowledges the growing sense of complexity, but nations have options in choosing to become subject to such law. Standards of evidence are of recurring controversy, and uncertainty in predictions has often engendered debate over the benefits of trade versus environmentally protective policy.

Causation—that is, irrefutable evidence that A causes B—with respect to sub-lethal effects of environmental exposure to chemicals, is practically impossible to obtain in human populations because of ethical restraints on controlled experimentation. Comprehensive statistical studies in epidemiology are not only prohibitively expensive, but also inevitably uncertain because of multiple confounders, including the variable mixtures of pollutants (which can be additive, non-additive, subtractive, or synergistic) found in human tissue. Developmental defects often do not become apparent or problematic until maturity, creating a lag time that also confounds conclusive studies in long-lived animals, including humans, especially where records have not been kept (Colborn et al. 1996).

The limitations of science for real-time analysis of environmental and human health phenomena have been recognized for many years, and the exploitation of uncertainty must be noted here. The implication that uncertainty means the science is necessarily weak is both erroneous and dangerously misleading (O'Brien 2000). Despite contrary interpretations of scientific findings, which provide evidence rather than proof, the scientific method is an excellent tool for collecting information.

A key step in managing uncertainty in ecosystem services is to realize that material cycling and energy flow are emergent properties of an ecosystem in that they result from both production and consumption components. Materials move through ecosystems in a cycle of production and consumption. The most important elements are carbon, hydrogen, and oxygen, which are required for photosynthesis; and nitrogen, phosphorous, sulphur, calcium, and magnesium, which are required for the construction of proteins and other structural compounds in the bodies of living organisms. These elements are transferred from soil and water to green plants when the plants grow (i.e., production). They are returned to soil and water whenever carbon chains are broken apart during consumption. Animals and some micro-organisms are consumers. Consumers use the carbon chains in their food as building blocks for their bodies. When consumers derive more mineral nutrients from their food than they need for their bodies, they release the extra minerals into their environment. Most micro-organisms are decomposers, who consume the bodies of dead plants, animals, and other micro-organisms to obtain the carbon-chain building blocks that they need for their growth. They release any surplus nutrients from their diet into the environment, where the nutrients are available for use by plants.

While the movement of materials in ecosystems is cyclic, the movement of energy is not cyclic. Energy enters ecosystems as sunlight and the energy is caught by photosynthesis in carbon chains that green plants use for the growth of their bodies. Plants break down some carbohydrates in their body (respiration) to get the energy they need for their own metabolism; and some of the energy is released into the environment as heat. The carbon chains that are left (i.e., photosynthesis minus plant respiration) are the carbon chains that plants have as building blocks for growth. The growth of all the plants in an ecosystem is the ecosystem’s net primary production. Primary production is the source of living material and energy (in the form of carbon compounds) for ecosystems.

When consumers use the carbon chains in their food as building blocks for their bodies, they break down some of the carbon chains to release energy for their metabolic needs. After consumers use the energy from respiration, the energy is then released into the environment as heat. As one consumer eats another, there is a flow of high-level energy in bonds of the carbon compounds through the food web. There is a loss of energy as heat when then energy is used at each step for metabolic work. The percentage of energy at any one step of a food chain that is available for consumption by the next step is called food chain efficiency. It is the energy in the food after metabolism, expressed as a percentage, and is typically 10–50% at each step of a food chain.

As molecules pass through the food web, carbon chains are broken apart, bit by bit, for energy until they disappear. When consumers respire, carbon dioxide and water are excreted; other minerals, in the form of plant nutrients such as nitrogen, phosphorous, potassium, magnesium, and calcium, are excreted in exactly the same form as when they entered the biological system. They cycle back to plants. Waste from consumers is food for producers. Energy does not cycle back to plants because energy leaves consumers as low-level heat, which plants cannot use. On a global scale, the sunlight energy that reaches Earth is eventually converted to low-level heat and leaves the Earth as infrared radiation.

Human energy inputs do not become part of the biological energy flow as does sunlight. Human energy inputs are used to organize ecosystems by changing the biological community and adding human-manufactured physical structures. This in turn affects biological energy flows and elemental cycling by changing primary production and the food web. Humans are dependent on the functioning of other parts of the ecosystem. As a species we are a consumer—just one among all the consumers in an ecosystem. Almost everything that people require for survival comes from the two essential services of material cycling and energy flow. Ecosystem services will decline if they are used too extensively. Over-exploration will deplete the ecosystem's resources (natural capital).

Examples of Biocomplexity in Environmental and Social Issues

POPs, Scientific Uncertainty, and International Law

While outcome predictions are inherently speculative, the presence of biologically active contaminants in biological tissue has demonstrated serious health consequences and justifies mitigating action. Without mitigation, the integrity of wild foods and mother's milk—in the North as elsewhere—will continue to be eroded by persistent organic pollutants, threatening all populations, especially in the Arctic, with unquantifiable risk.

The Arctic Monitoring and Assessment Program definition of "Arctic" is a region that includes much of the Subarctic (see fig. 2.2). Environments range from deep oceans to high alpine, with extensive open tundra, boreal forest, and wetland. The ocean is continually covered by pack ice that swells annually and is now rapidly shrinking in thickness and area. Much of the terrestrial Arctic is underlain by permafrost (continuous or discontinuous) that is warming or thawing, especially in Alaska and western Canada. Organisms that are highly adapted to Arctic seasonal cycles occupy Land and sea; many species use animal fat stores for energy and insulation through the long winter. Such a large area is difficult to generalize across, and variability is the rule; but many circumpolar realities justify classification of the area as a cohesive region. The landscapes and lifestyles tend to bare much in common: many plants and animals have a circumpolar range; and the lands and peoples that compose the Arctic are politically dominated by governments and interests of regions farther south.

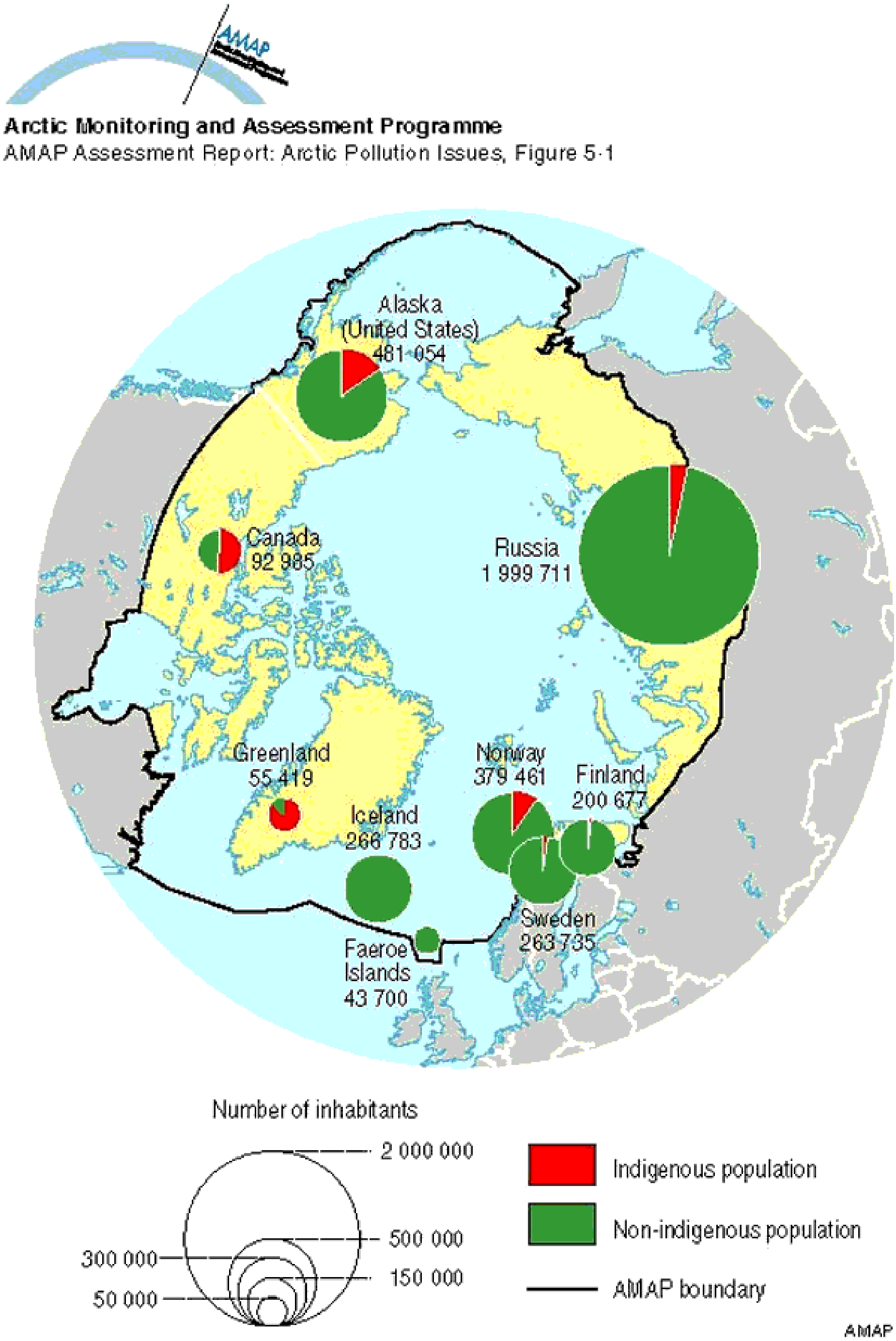

Fig. 2.2 Indigenous and non-indigenous populations in the Arctic as defined by AMAP

Arctic-specific considerations of fate and transport must include chemical behaviour in extreme and dynamic environments. Adsorption onto snow and ice particles, revolatilization during spring melt, variations of chemical behaviour in extreme cold, annual pulses of deposition, and bioavailability during spring runoff remain difficult to quantify.

Just as it took time for the ecological burden of organochlorines to shift north, so the benefits of legislation have been subject to a lag time. The recent AMAP report finds that Arctic accumulation of most of the 12 POPs listed in the Stockholm Convention is now slowing because of regulations imposed since the early 1970s (AMAP 2002). For example, the 209 polychlorinated biphenyls, which were banned in the United States for more than 30 years, are continuing to decline in most of the country, though they are still ubiquitous. The PCB levels in the Arctic are just beginning to decline, but some PCBs continue to accumulate high in the food webs of the North. Meanwhile, the levels of more recently recognized POPs, such as polybrominated flame retardants (PBFRs) are low but rapidly rising in the blood, fat, and breast milk of Arctic peoples. The relationships of stress and adaptation to anthropogenic stressors are more complex than current ecosystem response models can account for. These international problems thereby become social and legal issues. The dangers to the genetic, physiological, and cultural integrity of current and future generations gives Arctic peoples their claim to involvement in national and international policy decisions.

While modern chemistry has vastly improved the human condition in numerous ways, human populations who rely on the consumption of wild resources are paying the high cost of subsequent pollution: contaminated food. Arctic communities are not alone in experiencing disproportionate effects of disempowerment and pollution, but their position as a final endpoint of biomagnification puts them at particular risk.

Precaution is old advice: better safe than sorry. This paradigm of environmental law-making calls for the prevention of harm rather than its reparation (O’Brien 2000). Developed in response to the unpredictable risks of rapid climate change, and first broadly articulated as such in the Rio Declaration (UNEP 1992), the precautionary principle accounts for the irresolvable uncertainty of science by making a full understanding of serious risks a non-requisite to mitigating action. Human populations have long taken protective measures when they perceive serious risk, often despite a lack of detailed understanding of the potential danger.

An example of taking precautionary protective measures is Sweden. Sweden has long made health their very highest priority. All pesticide use that was not specifically approved was banned in the 1960s. In the early 1970s, Sweden began to require use of the least-toxic available alternative in any application, and a nationwide breast milk–monitoring program was initiated. Sweden intends that by 2007 all products on the market, including chemicals, will be free of substances that are persistent and liable to bioaccumulate.

The indigenous peoples of the circumpolar North are secondary consumers, quite literally at the top of the trophic food web; and, yet, the children of their children's children have an inherent right to an unpolluted food supply. While the physical and spiritual benefits of subsistence living are still thought to outweigh the risks of contaminants, health risks will become health problems unless there are improvements in the regulations of chemicals. Given the discoveries made by the Arctic Eight, especially by Norway and Canada, the international community agreed to work towards the "virtual elimination" of bioaccumulative toxic contaminants. The United Nations has crafted several international treaties for environmental protection. The Stockholm Convention, in articulating a commitment to legislate with foresight, is among those treaties that use precautionary language. The Stockholm Convention was designed to eliminate or restrict the production and use of POPs. The treaty targets 12 chemicals, but because these are only the most egregious contaminants, the treaty includes provisions to allow for the addition of "new" POPs—so that global regulation of the new compounds will take years, instead of decades. While chemical pollution will inevitably be an issue for decades to come, implementation of the Stockholm Convention will be a major step toward eliminating the toxic contaminants that threaten human progeny.

Biocomplex Effects of Bioterrorism

The concept of Gaia—formulated in 1965 by James Lovelock and further developed by Lynn Margulis—proposes that life on Earth grows, changes, and dies in ways that lead to the persistence of other life forms (Lovelock 1970; Margulis 1993). The Gaia hypothesis gives scientists both an organization hierarchy and a framework to assess the impact of bioterrorism on the environment. Starting with molecules, this framework extends with increasing complexity through organells, cells, tissues, individuals, populations, and ecosystems, finally involving the entire biosphere. While most scientists focus on one level of this hierarchy, it is the dynamic interactions between levels that maintain the feedback, resulting in a relatively constant or stable environment for life.

Some examples of the complexity of understanding possible threats to Alaska and the Arctic can be seen in human interactions with wildlife. Foot-and-mouth disease is a viral disease that propagates by contact or ingestion, as do many viral diseases. This disease spread in Europe during 2000 and 2001, requiring the destruction of cattle, which had both economic and psychological impacts. Adverse stress in mammals can predispose them to other diseases by weakening their immune response. The United States limited access to cattle and prevented the spread to the target species in the United States. In Europe, there may have been some spreading to wildlife populations; this is unknown at present. In

Alaska, access to captive wildlife was restricted so that the virus would not damage the wildlife by spreading to caribou herds. This policy decision was precautionary in nature and some effects on the tourist economy may have been incurred in order to protect the environment. In Alaska, where subsistence is a major way of life, people are more closely linked to the environment and its resources than in other areas of the world.

Another example of a vector affecting wildlife in the environment is mad cow disease (bovine spongiform encephalopathy, or BSE). BSE is a neurodegenerative wasting disease (spongiform encephalopathy) that is caused by an infectious particle called a “prion.” This wasting disease of the brain has been reported in sheep, cattle, mink, deer, cats, elephants, mice, and humans; and when it crossed the species barrier, it caused a small “epidemic” in Europe. This disease has “escaped” from research labs in the US Rocky Mountains and is believed to have infected wild herds of elk. The protective policy in Alaska seems well justified in hindsight.

The basis for prion diseases—like BSE in cows, scrapie in sheep, and Creutzfeldt-Jakob disease (CJD) in humans—is the cellular prion protein (PrPc), a naturally occurring protein found on surfaces of nerve cells in the brain. A beta structural form is able to convert normal protein into inactive aggregates. The beta variant form, which crossed species lines, is believed to have originated when cattle were given feed containing the ground remains of sheep infected with the brain ailment. Globalization of food supply is a complex system issue that must be a concern of policy-makers and may be a future target of bioterrorists.

For example, in Alaska there is concern that US food supplements may harbour BSE. Some dietary supplements contain imported extracts from brains or other organs of cattle that may have been exposed to BSE. Because BSE is transmitted by prions, such supplements may be of concern. Although the US Department of Agriculture has prohibited importation of tissues and organs from remnants from countries that have BSE, dietary supplements and cosmetics are not usually covered by their regulations.

Mad cow disease shows how a deadly pathogen can jump species to infect humans. This pathogen, the prion, is radically different from a bacterium (like anthrax) and a virus (like foot-and-mouth disease), as it is hard to destroy, even by sterilization. If animals are destroyed, the prion can stay in the environment for many years, as seen in the Rocky Mountains case. Methods to destroy prions and to sterilize potentially contaminated environments are needed.

Another example of a wildlife or livestock pathogen that occurs around the world and occasionally causes small outbreaks of infection and death is anthrax. Anthrax has been used in bioterrorism as a biological weapon in a form that has a higher concentration of spores, which improves its delivery to target tissues, the lungs. Since anthrax is spread through direct contact with anthrax spores, an individual has to touch, inhale, or eat it in order to contract the disease. Fortunately, since anthrax is a bacterium, it can be treated with antibiotics or prevented by vaccination. There is always a small risk of side effects from these therapies. Vaccination, which is expensive, is not routinely carried out throughout the whole population. In fact, smallpox did not become a biological weapon until the United States stopped its vaccination program.

The Exxon Valdez oil spill was not an act of bioterrorism, unlike the oil spill in the Persian Gulf, where Iraq tried to destroy the environment—that is, the freshwater supply—of its enemy. Although it was unintended, the Exxon Valdez oil spill resulted in loss of wildlife, such as birds and marine mammals. Some species, such as river otters, have recovered; others, such as sea otters, have not. This oil spill affected animals by directly damaging their immune system or indirectly removing their food supply. Unintended effects of chemical and biological weapons used by terrorists would also cause vast damage to the environment.

A potential future feedback issue related to bioterrorism could be that our values of freedom and tolerance would conflict with those values supporting repression and safety. Repression is commonly used as a means to personal power. The negative effect of the personal power of the human species on the biosphere is well documented. History has recorded many events that have had unintended environmental effects. A secondary effect of bioterrorism could be changes in distribution of fish and wildlife, which in turn affect subsistence consumers. This would be a secondary effect on food production caused by “collateral damage” from bioweapons that were intended for man but were non-specific enough to affect plants and wildlife.

Bioindicators for Monitoring Arctic and Subarctic Environmental Systems

Subtle changes in the environment that affect vital resources such as air quality, the quantity or quality of fresh water, and the distribution and assemblages of native and introduced species may have profound effects on human, animal, and plant health. There have been many examples of the disastrous, unintended effects of human actions. The study of the feedbacks between human health and the environment must therefore be comprehensive, including research on the long-term shifts in ecological and human health, as well as the effects of extreme events.

Contaminants create a serious health problem in the Arctic because they strongly affect the traditional way of life of the indigenous peoples. The contaminants have a tendency to accumulate in certain animals, especially marine mammals used as traditional food by indigenous people. Thus, the exposure to contaminants is closely connected to consumption of traditional food. It is not difficult to predict that the psychological effect of describing traditional food as “dangerous” could be strong and have a negative effect on traditional ways of life among the indigenous peoples. If this happens, the contaminants will impact mental health.

The principal heavy metals of concern in the Arctic are mercury, lead, and cadmium. Human exposure to mercury is closely related to traditional food, especially of marine origin. Mercury in the diet is in the methylated state. Methyl mercury is a neurotoxic compound that can pass the placental barrier and can be excreted through milk, placing fetuses and breastfed children at risk.

Human exposure to radionuclides is still a concern, even if such exposure has declined since the cessation of above-ground nuclear testing. The Arctic’s terrestrial system is more vulnerable to manufactured radioactive contamination than are the temperate areas. The handling and storage of spent nuclear fuel is of major importance in the context of threats to the Arctic environment. The risk of accidents in functioning nuclear power plants also causes concern in some parts of the Arctic.

Burger and colleagues have suggested that bioindicators can be used to monitor the changes in the status of ecosystems or to evaluate remediation efforts. Bioindicators usually refer to organisms and their properties as components of an ecosystem. Both ecology and society benefit by relevant bioindicators. Table 2.2 summarizes the characteristics of good bioindicators.

Table 2.2 Characteristics of bioindicators (from Burger)

Biological relevance:	• Exhibits changes in response to stress • Intensity of changes relate to intensity of stressors • Changes are biologically important and occur early enough to prevent catastrophic effects.
Methodological relevance:	• Easy to use in the field, and easy to interpret • Can be used to test management questions • Can be used to test hypotheses
Societal relevance:	• Of interest to the public • Easily understood by the public • Transparent to the public • Measures aspects of environment that relate to human health or ecological services provided by the environment

Healthy ecosystems need to be maintained to ensure they receive services from the ecosystems. Bioindicators that indicate both organismal and human health are desirable. Carnivores such as river otters or other top-level carnivores have been useful bioindicators. There is a need to select common and widespread species as bioindicators because their populations can be monitored and stresses measured. Bioindicator species should also provide insight into both the functional and structural aspects of a healthy ecosystem. Some common structural and functional end points at the community and ecosystem level are summarized in table 2.3.

Table 2.3 Common structural and functional end points

Structural end points:	• Species richness • Species abundance
Functional end points:	• Rate of primary productivity • Rate of nutrient uptake/regeneration • Rate of pollution export • Rate of recovery after stress

Species that are higher on the Arctic food chain are more comparable to humans and most sensitive to stressors such as mercury. For example, river otters and humans both eat fish. Indicator species lower on the food chain can suggest potential damage to higher trophic level organisms within ecosystems. See figure 2.3.

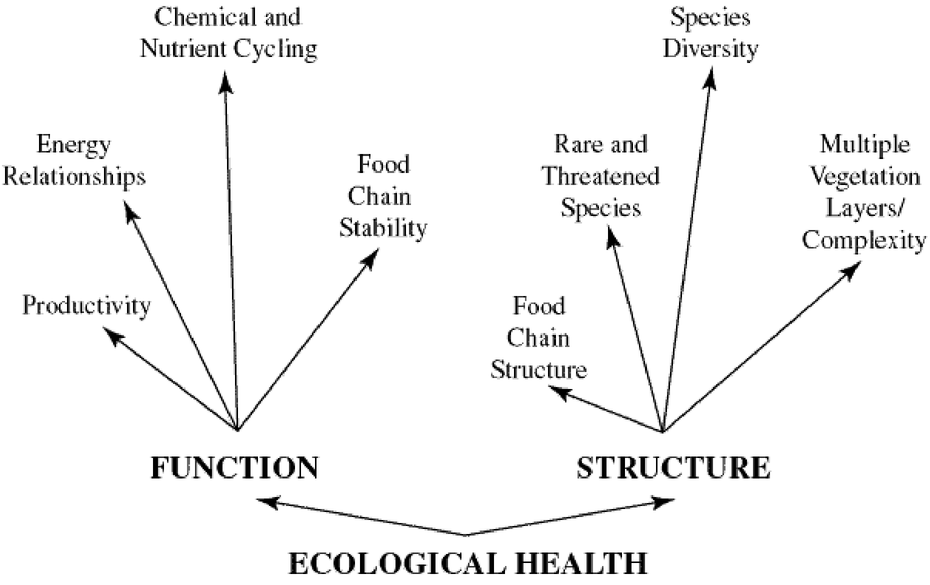

Fig. 2.3 A schematic of ecosystem health

Figure 2.4 is a schematic of bioindicator properties for river otter. Measurement of populations or of reproductive variables, physiologic condition, growth, or contaminant levels can serve as bioindicators.

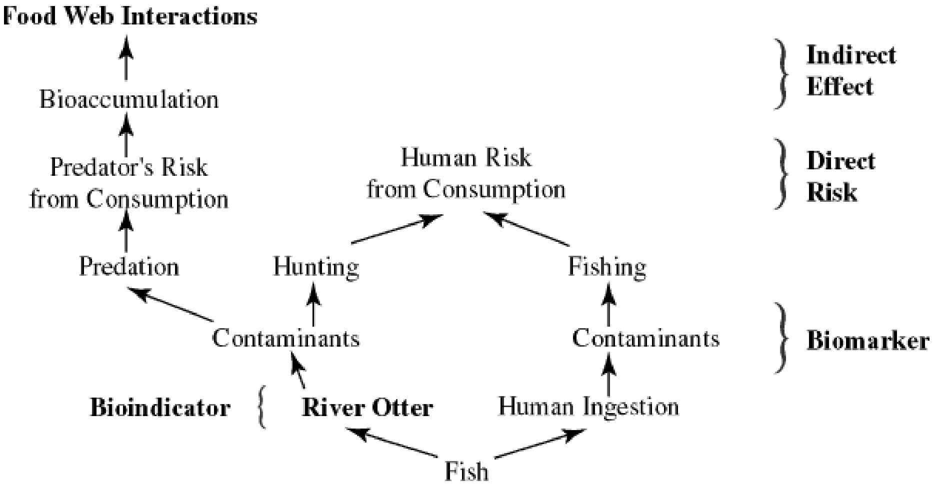

Fig. 2.4 Bioindicator properies for river otter

Table 2.4 suggests possible bioindicators at different organizational levels for Arctic and Subarctic systems.

Table 2.4 Bioindicators for monitoring Arctic and Subarctic systems

Ecological Level	**Indicators/Metrics**	**Rationale**
Individual Species	Duck	Common; abundant; widespread; eaten by higher trophic levels, including predatory birds and humans
	River otter or sea otter	Represents higher trophic level; eaten by other predators, including humans
Populations	Colonial water birds	Of interest to the public; vulnerable because they breed and feed in aquatic habitats that concentrate toxins
	Small mammals	Of less interest to the public, but extremely common around polluted sites
Community	Salmon and freshwater fish	Of interest to the public; vulnerable because they are aquatic
	Lichen and plants	Low trophic level and thus indicative of higher-level effects; measures effects in terrestrial systems
Ecosystem	Species diversity	Of interest to the public; easy to understand and interpret; can be used over time; diversity can be measured for indicator groups of species
Landscape	Per cent habitat	Of interest to the public because changes are easy to see and understand; can be used to assess quality of habitat as well as temporal changes

All environments are subject to change, natural change, and change manufactured by humans; indeed, the geological record testifies to the nature and magnitude of these changes—over which the human race has no long-term control. In relation to climate change, these changes are already obvious. But still developers build houses on flood plains; and areas doomed to frequent flooding are protected by human ingenuity, though only for a limited period of time and at high cost.

As a result of diverse events such as drought, flooding, climatic change, wars, disease, and economic decline, large numbers of people will migrate on a large scale. As seen in table 2.4, community and ecosystem changes will have a major impact on the Arctic and Subarctic. Other major issues of concern include the following:

1. The fish stocks have declined in relation to fishing practices, and the virtual loss of native salmon and trout because of fish farms. They have had major impacts upon the marine environment, which in many ways go unnoticed (i.e., no measures were taken at the appropriate time to reduce the impact because of economic reasons or lack of scientific information).
2. With respect to farming practices, plants have been removed to accommodate large-scale farming machinery with the result of loss of habitats.
3. Plants that survived are affected by agricultural chemicals and the unknowns of genetically modified plants.
4. There are changes yet to come from the effects of gradual change in climate and weather systems.
5. The association between air quality and asthma, especially in the young, is of international concern; but priorities are often set as dictated by disciplinary needs rather than by possible practical issues.

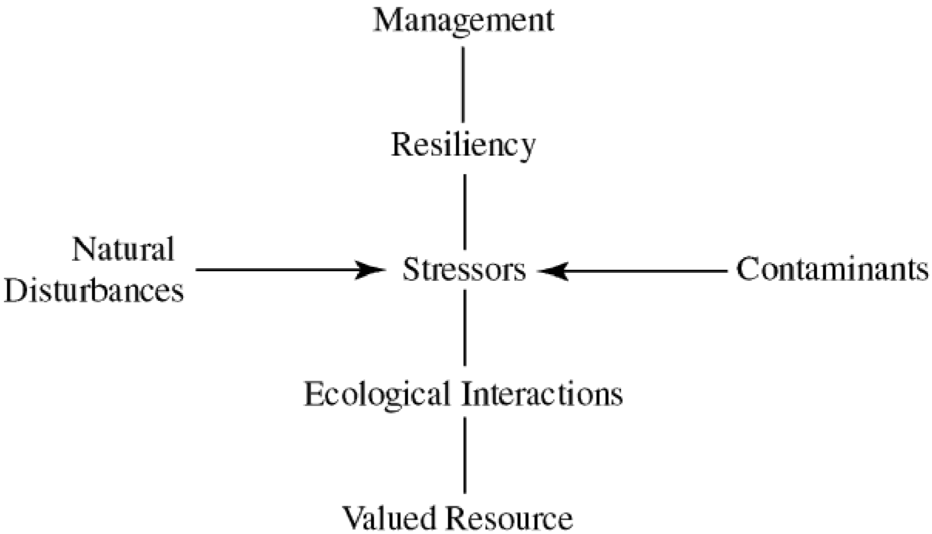

Fig. 2.5 A conceptual model of stewardship

Study Questions

1. What is the significance of positive and negative feedback?
2. List examples of using positive feedback to make desired changes.
3. How do emergent properties arise from the hierarchical organization of systems?
4. Describe the complex environmental system cycles in terms of material and energy cycling.
5. Illustrate the effect of human-induced changes on ecosystem services.
6. Identify bioindicators and biomarkers of human and ecological health.

Glossary of Terms

biome	a large-scale ecosystem associated with a particular climatic region.
biocomplex systems	systems with feedback loops that enable them to adjust to fluctuations in the environment in ways that promote their survival.
bioindicator (or biomonitor)	the use of organisms to monitor contamination and to imply possible effects to biota or routes of toxicant to human. Also called BIOMONITOR.
boomerang paradigm	that which you throw away can come back to hurt you.
carrying capacity	the maximum population size of a particular plant or animal species that an ecosystem can support on a long-term basis.
chemical cycles	the circulation in an ecosystem of chemical elements through the soil, water, air, and food web. Also called MATERNAL CYCLES.
community assembly	the self-organization of a biological community by selective addition of new species that arrive in an ecosystem.
ecosystem	the functional unit of ecology including both the biotic community and its abiotic components, functioning together to direct the flow of energy and cycling of materials.

ecosystem services	materials and energy that living organisms obtain from ecosystems for survival or experience that enrich the lives of humans.
ecotone	the area of transition between two or more community types.
ecotoxicology	the science of contaminants in the biosphere and their effects on organisms in the ecosystem.
elasticity	the ability of a community to return to its pre-stressed condition.
emergent properties	properties in a hierarchical system that came into existence from the organization of the system’s parts rather than from characteristics of any of the parts themselves. They cannot be predicted from our understanding of the system’s parts or components alone.
energy flow	the movement of energy in the carbon chains of organic matter that passes through a food web as one organism consumes another.
food chain	a series of living organisms connected by one eating another.
food web	a set of interconnected food chains that includes all the organisms in an ecosystem.
Gaia hypothesis	Earth’s weather and chemistry are homeostatically regulated by the sum of all the biota.
hierarchical organization	the organization of a system in such a way that each element of the system contains other elements within it.
homeostasis	negative feedback that maintains a living organism’s body functions within limits in spite of external stimuli that have created a stress to disrupt function.
landscape	the sum total aspect of any geographical area.
natural capital	all the natural resources on which a civilization depends to create prosperity.
negative feedback	a chain of effects through an ecosystem or social system that tends to keep particular parts of the system within certain limits.
niche	the role of a particular species in the ecosystem. It is defined in terms of the conditions and resources necessary for the survival of the species as well as the position of the species in the food web.

over-exploration	use of an ecosystem service on a long-term basis in excess of what the ecosystem can sustain.
positive feedback	a chain of effects through a system that amplifies change.
precautionary principle	proposes prudent action though there is a limited knowledge of the environment.
resilience	the ability to return to the original form after severe stress or disturbance.
social institutions	established patterns of behaviour or relationships accepted as a fundamental part of a culture.
stability domain	a set of similar system states characterized by natural or social processes that tend to keep the system in those states.
values	the emotionally respected ideals, customs, and institutions of a society.
world view	a person's comprehensive conception or image of the surrounding world and his relation to it.

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