**Four Laws of Ecology**

(Excerpts)

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1 In broad outline, these are the environmental cycles which govern the behavior of the three great global systems: the air, the water, and the soil. Within each of them live many thousands of different species of living things. Each species is suited to its particular environmental niche, and each, through its life processes, affects the physical and chemical properties of its immediate environment.

2 Each living species is also linked to many others. These links are bewildering in their variety and marvelous in their intricate detail. An animal, such as a deer, may depend on plants for food; the plants depend on the action of soil bacteria for their nutrients; the bacteria in turn live on the organic wastes dropped by the animals on the soil. At the same time, the deer is food for the mountain lion. Insects may live on the juices of plants or gather pollen from their flowers. Other insects suck blood from animals. Bacteria may live on the internal tissues of animals and plants. Fungi degrade the bodies of dead plants and animals. All this, many times multiplied and organized species by species in intricate, precise relationships, makes up the vast network of life on the earth.

3 The science that studies these relationships and the processes linking each living thing to the physical and chemical environment is ecology. It is the science of planetary housekeeping. For the environment is, so to speak, the house created on the earth by living things for living things. It is a young science and much of what it teaches has been learned from only small segments of the whole network of life on the earth. Ecology has not yet explicitly developed the kind of cohesive, simplifying generalizations exemplified by, say, the laws of physics. Nevertheless there are a number of generalizations that are already evident in what we now know about the ecosphere and that can be organized into a kind of informal set of “laws of ecology.” These are described in what follows.

**The First Law of Ecology:**

**Everything Is Connected to Everything Else**

4 Some of the evidence that leads to this generalization has already been discussed. It reflects the existence of the elaborate network of interconnections in the ecosphere: among different living organisms, and between populations, species, and individual organisms and their physicochemical surroundings.

5 The single fact that an ecosystem consists of multiple interconnected parts, which act on one another, has some surprising consequences. Our ability to picture the behavior of such systems has been helped considerably by the development, even more recent than ecology, of the science of cybernetics. We owe the basic concept, and the word itself, to the inventive mind of the late Norbert Wiener.

6 The word “cybernetics” derives from the Greek word for helmsman; it is concerned with cycles of events that steer, or govern, the behavior of a system. The helmsman is part of a system that also includes the compass, the rudder, and the ship. If the ship veers off the chosen compass course, the change shows up in the movement of the compass needle. Observed and interpreted by the helmsman this event determines a subsequent one: the helmsman turns the rudder, which swings the ship back to its original course. When this happens, the compass needle returns to its original, on-course position and the cycle is complete. If the helmsman turns the rudder too far in response to a small deflection of the compass needle, the excess swing of the ship shows up in the compass—which signals the helmsman to correct his overreaction by an opposite movement. Thus the operation of this cycle stabilizes the course of the ship.

7 In quite a similar way, stabilizing cybernetic relations are built into an ecological cycle. Consider, for example, the fresh-water ecological cycle: fish—organic waste—bacteria of decay—inorganic products—algae—fish. Suppose that due to unusually warm summer weather there is a rapid growth of algae. This depletes the supply of inorganic nutrients so that two sectors of the cycle, algae and nutrients, are out of balance, but in opposite directions. The operation of the ecological cycle, like that of the ship, soon brings the situation back into balance. For the excess in algae increases the ease with which fish can feed on them; this reduces the algal population, increases fish waste production, and eventually leads to an increased level of nutrients when the waste decays. Thus, the levels of algae and nutrients tend to return to their original balanced position.

8 In such cybernetic systems the course is not maintained by rigid control, but flexibly. Thus the ship does not move unwaveringly on its path, but actually follows it in a wavelike motion that swings equally to both sides of the true course. The frequency of these swings depends on the relative speeds of the various steps in the cycle, such as the rate at which the ship responds to the rudder.

9 Ecological systems exhibit similar cycles, although these are often obscured by the effects of daily or seasonal variations in weather and environmental agents. The most famous examples of such ecological oscillations are the periodic fluctuations of the size of fur-bearing animal populations. For example, from trapping records in Canada it is known that the populations of rabbits and lynx follow ten-year fluctuations. When there are many rabbits the lynx prosper; the rising population of lynx increasingly ravages the rabbit population, reducing it; as the latter become scarce, there is insufficient food to support the now numerous lynx; as the lynx begin to die off, the rabbits are less fiercely hunted and increase in number. And so on. These oscillations are built into the operation of the simple cycle, in which the lynx population is positively related to the number of rabbits and the rabbit population is negatively related to the number of lynx.

10 In such an oscillating system there is always the danger that the whole system will collapse when an oscillation swings so wide of the balance point that the system can no longer compensate for it. Suppose, for example, in one particular swing of the rabbit–lynx cycle, the lynx manage to eat all the rabbits (or, for that matter, all but one). Now the rabbit population can no longer reproduce. As usual, the lynx begin to starve as the rabbits are consumed; but this time the drop in the lynx population is not followed by an increase in rabbits. The lynx then die off. The entire rabbit–lynx system collapses.

11 This is similar to the ecological collapse which accompanies what is called “eutrophication.” If the nutrient level of the water becomes so high as to stimulate the rapid growth of algae, the dense algal population cannot be long sustained because of the intrinsic limitations of photosynthetic efficiency. As the thickness of the algal layer in the water increases, the light required for photosynthesis that can reach the lower parts of the algal layer becomes sharply diminished, so that any strong overgrowth of algae very quickly dies back, releasing organic debris. The organic matter level may then become so great that its decay totally depletes the oxygen content of the water. The bacteria of decay then die off, for they must have oxygen to survive. The entire aquatic cycle collapses.

12 The dynamic behavior of a cybernetic system—for example, the frequency of its natural oscillations, the speed with which it responds to external changes, and its over-all rate of operation—depends on the relative rates of its constituent steps. In the ship system, the compass needle swings in fractions of a second; the helmsman’s reaction takes some seconds; the ship responds over a time of minutes. These different reaction times interact to produce, for example, the ship’s characteristic oscillation frequency around its true course.

13 In the aquatic ecosystem, each biological step also has a characteristic reaction time, which depends on the metabolic and reproductive rates of the organisms involved. The time to produce a new generation of fish may be some months; of algae, a matter of days; decay bacteria can reproduce in a few hours. The metabolic rates of these organisms—that is, the rates at which they use nutrients, consume oxygen, or produce waste—is inversely related to their size. If the metabolic rate of a fish is 1, the algal rate is about 100, and the bacterial rate about 10,000.

14 If the entire cyclical system is to remain in balance, the over-all rate of turnover must be governed by the slowest step—in this case, the growth and metabolism of the fish. Any external effect that forces part of the cycle to operate faster than the over-all rate leads to trouble. So, for example, the rate of waste production by fish determines the rate of bacterial decay and the rate of oxygen consumption due to that decay. In a balanced situation, enough oxygen is produced by the algae and enters from the air to support the decay bacteria. Suppose that the rate at which organic waste enters the cycle is increased artificially, for example, by dumping sewage into the water. Now the decay bacteria are supplied with organic waste at a much higher level than usual; because of their rapid metabolism they are able to act quickly on the increased organic load. As a result, the rate of oxygen consumption by the decay bacteria can easily exceed the rate of oxygen production by the algae (and its rate of entry from the air) so that the oxygen level goes to zero and the system collapses. Thus, the rates of the separate processes in the cycle are in a natural state of balance which is maintained only so long as there are no external intrusions on the system. When such an effect originates outside the cycle, it is not controlled by the self-governing cyclical relations and is a threat to the stability of the whole system.

15 Ecosystems differ considerably in their rate characteristics and therefore vary a great deal in the speed with which they react to changed situations or approach the point of collapse. For example, aquatic ecosystems turn over much faster than soil ecosystems. Thus, an acre of richly populated marine shoreline or an acre of fish pond produces about seven times as much organic material as an acre of alfalfa annually. The slow turnover of the soil cycle is due to the rather low rate of one of its many steps—the release of nutrient from the soil’s organic store, which is very much slower than the comparable step in aquatic systems.

16 The amount of stress which an ecosystem can absorb before it is driven to collapse is also a result of its various interconnections and their relative speeds of response. The more complex the ecosystem, the more successfully it can resist a stress. For example, in the rabbit—lynx system, if the lynx had an alternative source of food they might survive the sudden depletion of rabbits. In this way, branching—which establishes alternative pathways—increases the resistance of an ecosystem to stress. Most ecosystems are so complex that the cycles are not simple circular paths, but are crisscrossed with branches to form a network or a fabric of interconnections. Like a net, in which each knot is connected to others by several strands, such a fabric can resist collapse better than a simple, unbranched circle of threads—which if cut anywhere breaks down as a whole. Environmental pollution is often a sign that ecological links have been cut and that the ecosystem has been artificially simplified and made more vulnerable to stress and to final collapse.

17 The feedback characteristics of ecosystems result in amplification and intensification processes of considerable magnitude. For example, the fact that in food chains small organisms are eaten by bigger ones and the latter by still bigger ones inevitably results in the concentration of certain environmental constituents in the bodies of the largest organisms at the top of the food chain. Smaller organisms always exhibit much higher metabolic rates than larger ones, so that the amount of their food which is oxidized relative to the amount incorporated into the body of the organism is thereby greater. Consequently, an animal at the top of the food chain depends on the consumption of an enormously greater mass of the bodies of organisms lower down in the food chain. Therefore, any nonmetabolized material present in the lower organisms of this chain will become concentrated in the body of the top one. Thus, if the concentration of DDT (which is not readily metabolized) in the soil is 1 unit, earthworms living in the soil will achieve a concentration of from 10 to 40 units, and in woodcocks feeding on the earthworms the DDT level will rise to about 200 units.

18 All this results from a simple fact about ecosystems—everything is connected to everything else: the system is stabilized by its dynamic self-compensating properties; these same properties, if overstressed, can lead to a dramatic collapse; the complexity of the ecological network and its intrinsic rate of turnover determine how much it can be stressed, and for how long, without collapsing; the ecological network is an amplifier, so that a small perturbation in one place may have large, distant, long-delayed effects.

The Second Law of Ecology:

Everything Must Go Somewhere

19 This is, of course, simply a somewhat informal restatement of a basic law of physics—that matter is indestructible. Applied to ecology, the law emphasizes that in nature there is no such thing as “waste.” In every natural system, what is excreted by one organism as waste is taken up by another as food. Animals release carbon dioxide as a respiratory waste; this is an essential nutrient for green plants. Plants excrete oxygen, which is used by animals. Animal organic wastes nourish the bacteria of decay. Their wastes, inorganic materials such as nitrate, phosphate, and carbon dioxide, become algal nutrients.

20 A persistent effort to answer the question “Where does it go?” can yield a surprising amount of valuable information about an ecosystem. Consider, for example, the fate of a household item which contains mercury—a substance with serious environmental effects that have just recently surfaced. A dry-cell battery containing mercury is purchased, used to the point of exhaustion, and then “thrown out.” But where does it really go? First it is placed in a container of rubbish; this is collected and taken to an incinerator. Here the mercury is heated; this produces mercury vapor which is emitted by the incinerator stack, and mercury vapor is toxic. Mercury vapor is carried by the wind, eventually brought to earth in rain or snow. Entering a mountain lake, let us say, the mercury condenses and sinks to the bottom. Here it is acted on by bacteria which convert it to methyl mercury. This is soluble and taken up by fish; since it is not metabolized, the mercury accumulates in the organs and flesh of the fish. The fish is caught and eaten by a man and the mercury becomes deposited in his organs, where it might be harmful. And so on.

21 This is an effective way to trace out an ecological path. It is also an excellent way to counteract the prevalent notion that something which is regarded as useless simply “goes away” when it is discarded. Nothing “goes away”; it is simply transferred from place to place, converted from one molecular form to another, acting on the life processes of any organism in which it becomes, for a time, lodged. One of the chief reasons for the present environmental crisis is that great amounts of materials have been extracted from the earth, converted into new forms, and discharged into the environment without taking into account that “everything has to go somewhere.” The result, too often, is the accumulation of harmful amounts of material in places where, in nature, they do not belong.