Input Management of Production Systems

EUGENE P. ODUM

Nonpoint sources of pollution, which are largely responsible for stressing regional and global life-supporting atmosphere, soil, and water, can only be reduced (and ultimately controlled) by input management that involves increasing the efficiency of production systems and reducing the inputs of environmentally damaging materials. Input management requires a major change, an about-face, in the approach to management of agriculture, power plants, and industries because the focus is on waste reduction and recycling rather than on waste disposal. For large-scale ecosystem-level situations a top-down hierarchical approach is suggested and illustrated by recent research in agroecology and landscape ecology.

I SUGGESTED PREVIOUSLY THAT ECOLOGY WAS EMERGING AS A new integrative discipline dealing with the total environmental system in which we live and that it must combine holism and reductionism if its applications are to benefit society (*1*). Hierarchical theory (*2, 3*) provides a promising basis for this integration. The assumption is that complex systems such as ecosystems are hierarchical in structure and function and are best understood in terms of levels of organization within the total system. Because ecosystems are thermodynamically far-from-equilibrium open systems where processes at lower levels are constrained by those at higher levels, what is called a "top-down" or "outside-to-inside" approach (*4*) is suggested in which externals are considered first, then the internals. One first delimits an area, a system, or a problem as a sort of "black box." Then, energy, material, and organism inputs and outputs, and major functional processes (primary production, for example) of the system as a whole are examined. Following this principle, one then examines those components and processes (populations, internal cycles and feedbacks, and food webs) that are operationally significant by observing, modeling, or perturbing the system.

Applied scientists have been slow to use the holistic top-down approach to environmental problems. One reason is that "piecemeal" or "quick-fix" approaches often work well in the short term of economic and political worlds. For example, increasing the height of smokestacks alleviates local air pollution, which "solves" the problem as far as local citizens and governments are concerned but increases acid rain and other pollution at the regional level. When numbers of "quick fixes" are made independently, the central problem is not properly addressed. Economist Alfred Kahn has termed this situation the "tyranny of small decisions" (*5*). Science in general has become so reductionist that society is victimized by a "tyranny of small technologies" that arise from increasing specialization and the preoccupation with laboratory study. The open systems of real-world environments cannot be enclosed in glass tubes or laboratory walls. These thermodynamically nonequilibrium systems require strong inflows of high-quality energy and a means of dissipating disorder if they are to survive, evolve, and improve. They cannot be dealt with one piece at a time or in isolation from economic and political considerations that underlie management decisions. A more holistic way of thinking and action must be adopted to reduce global stresses such as atmospheric toxification that are increasing in intensity and scale.

Pollution Stress on Life-Support Systems

Because life support is provided by a vast network of processes involving activities of organisms (plants and microbes especially) that operate on different time scales, one cannot simply go into the environment and point and say, "There is our life-support system ticking away." Yet the basic ecosystems that provide life support can be readily identified, which is vital if they are to be recognized and preserved. In terms of the landscape as a whole, as viewed from an airplane or satellite, agricultural systems plus natural systems equal life-support systems. The former provide the 1 million calories and 15% protein required by each person per year. Natural systems, such as oceans, rivers, forests, and grasslands, provide the other physiological necessities by purifying and recycling air and water and by stabilizing climates.

As defined here, the natural environment consists of areas of the biosphere that are self-maintaining in that they operate without energetic or economic flows controlled by humans, even though they may be impacted in various ways by human activities. These are the basic solar-powered systems dependent on sunlight and other indirect forms of solar energy such as rainfall and water flow. They are low powered, so large areas are required to support high-powered, human-made, energy-intensive, urban-industrial development. Energy density, that is, energy flow per unit of area may be several orders of magnitude greater in a large urban area than in the surrounding life-supporting countryside (*6*).

Pollution has been a local problem since the dawn of civilization, but especially since the industrial revolution. However, for the first time in history, pollution resulting from human activities is becoming global in scale and a widespread threat to life-support ecosystems. Pollution can be considered under two headings: point-source pollution wastes and toxic substances that enter the environment through pipes and ditches, and nonpoint pollution originating from numerous scattered or diffuse sources, such as automobile exhausts and runoff from agricultural fields. In recent years considerable progress has been made in reducing municipal and industrial point-source pollution, but nonpoint pollution has been increasing, as documented by Smith, Alexander, and Wolman in their review of

The author is Callaway Professor of Ecology Emeritus and director emeritus of the Institute of Ecology, University of Georgia, Athens, GA 30602. This article is adapted from an address given at the Crafoord Lectures in Stockholm, Sweden, in September 1987, when the author and his brother, Howard T. Odum, received the Crafoord Prize, awarded by the Royal Swedish Academy of Sciences. The lecture given by H. T. Odum was published in the 25 November 1988 issue of *Science*.

water quality in the nation's rivers (7). Contamination of surface and ground water by agricultural and industrial chemicals; soil erosion from both rural and urban landscapes; increases in greenhouse gases, acid rain, and ground-level ozone; reduction in protective ozone stratisferic layers; and other forms of atmospheric toxification currently pose the greatest threat to earth's life-supporting atmosphere, soil, and water.

These nonpoint pollution sources, unlike point sources, cannot be controlled from the output side of production systems; they can only be controlled from the input side by what I call input management. Input management requires a major change, an about-face, in the philosophy and technology of management of agriculture, power plants, industrial plants, and other production systems.

Attention for many years has focused on increasing outputs, that is, yields. Whatever inputs that would increase yield on the short term were provided with little regard to efficiency or production of unwanted outputs such as nonpoint pollution. From both environmental and monetary standpoints, attention now needs to be shifted to the input side of the production system (Fig. 1). By increasing the efficiency of current wasteful systems, costly and environmentally damaging inputs can be reduced with concurrent reduction in nonpoint pollution and without much sacrifice in yields of food, electricity, or manufactured goods. The profit margin should also increase as input costs are reduced.

I suggest that technologists and politicians are approaching pollution problems from the "wrong end." For example, there is no economically affordable technological solution for dealing with the ever-increasing wastes coming out of New York City. Long-term sustainable solutions are to be found in waste reduction and recycling rather than waste disposal. Examples from agroecology and landscape ecology illustrate the top-down approach and the potential for input management.

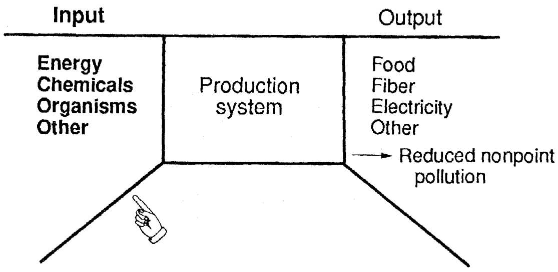

Fig. 1. The approach to the management of production systems. The current focus is on output, that is, yield, with consequences of increased nonpoint source pollution. The shift to input management with focus on efficiency and reduction of environmentally damaging inputs so as to reduce nonpoint pollution is indicated by the pointing finger. [Adapted from (30) with permission © 1987, Soil and Water Conservation Society]

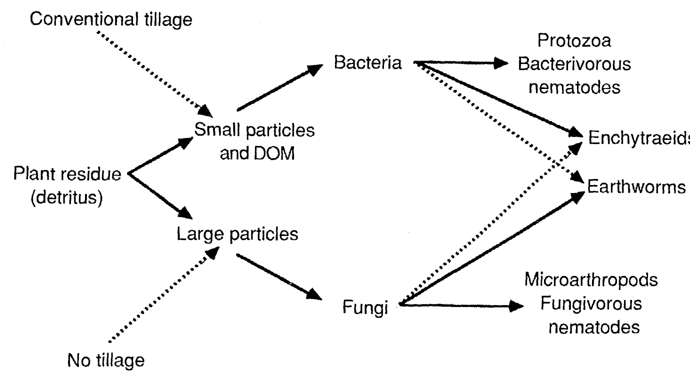

Fig. 2. Comparison of detrital food chains in CT and NT agricultural systems. DOM, dissolved organic matter.

Reduced Input Agriculture

Recent trends in farm system husbandry indicate that reduced input agriculture is being researched and practiced, which is good news for the future of earth's life-support systems. During the past several decades increases in the yield of grain and other cash crops have been obtained partly by selection of high-yielding cultivars but mostly by vast increases in the inputs of machine energy, fertilizers, irrigation water, and pesticides. In general, crop yields have leveled off during the past 10 years, indicating that diminishing returns are being reached for this output management that involves massive energy and chemical inputs. Increasing profits simply by increasing yield becomes a less viable strategy when costs of input subsidies rise or market prices fall.

Most important of all, increased use of agricultural chemicals in continuous monocultures produces an unwanted increase in nonpoint pollution, not only by chemicals but by soil as well. In Illinois, soil losses and runoff of toxic chemicals from continuous grain and soybean monocultures are producing a stress on the Illinois River greater than when raw sewage from Chicago was dumped into the river many years ago (8). By 1975 it was estimated that 25 million tons of soil laced with chemicals was moving annually from farmland into this river, most of it settling into the shallow lakes and lagoons that are such an important part of this productive river basin (8). Elsewhere, soil and chemical runoff are creating havoc in lakes, coastal waters, and estuaries such as San Francisco Bay (9). Again, one sees the shortcomings of the piecemeal approach in that efforts to enhance one part of the life-support environment (agriculture) are degrading other equally vital components (natural systems).

Conservation tillage practices—crop-planting systems that leave 30% or more of crop residues on the soil surface instead of plowing them under—are examples of reduced input practices that decrease unwanted outputs. These practices range from ridge tillage, appropriate for cooler regions, to no tillage (NT), which is especially effective in warm and dry regions. In the hilly piedmont region of Georgia, annual soil losses under conventional tillage (CT) (deep moldboard plowing twice a year) are estimated at 25 to 40 metric tons per hectare, and nitrogen losses at 10 to 15 kg/hectare (10). No tillage combined with winter clover and rye (the latter to provide mulch) can greatly reduce both soil and nitrate losses (11). Where water is scarce or expensive, maintaining a layer of mulch can greatly increase water retention (12). Theoretically, soil quality is improved under conservation tillage rather than slowly degraded as is often the case with CT, but conservation tillage has not been in place long enough to determine if increased sustainability will work in large-scale, long-term practice. Cropland under various forms of conservation tillage is increasing rapidly in the United States, with one-third of cropland managed in this way as of 1985 (13).

Reduced input agriculture in its various forms (for example, conservation tillage, organic farming, and regenerative agriculture) is not without problems. Special equipment is required to plant in unplowed, heavily mulched soil. Integrated pest control procedures for both weeds and insects need to be applied if the input of herbicides and pesticides is to be reduced. Management of reduced input agriculture is definitely more sophisticated than in the case of CT. The farmer cannot just plant, fertilize, spray, and then sit on the porch until it is time to harvest. Additional research, especially on long-term experimental plots, is needed.

The challenge to the new generation of biotechnologists is to genetically engineer cultivars that are not just high yielding but are more efficient and require less fertilizer, pesticides, and other environmentally damaging chemicals. The means are available to quickly engineer back in the "antiherbivore" mechanisms present in the wild ancestors. These were bred out in the past in order to increase yields and on the assumption that externally applied insecticides would take the place of the evolved internal natural defenses.

Critical Organizing Centers and Detrital Food Webs in Agroecosystems

With the top-down approach, researchers need to consider how components and processes within the crop field are affected by changes in inputs and outputs. For the past 10 years a team of agroecologists at the University of Georgia has been researching the effect of different planting systems on basic ecological processes such as nutrient cycling, community metabolism, food webs, and decomposition (*14*). In terrestrial ecosystems, both natural and domesticated, the litter-soil zone functions as a critical organizing center that controls internal functions of the ecosystem. It is in the detrital food web that the rate and chemical nature of decomposition are determined, which in turn specify the quantity and quality of nutrients available for uptake by autotrophs. Theoretically, not only the pattern of primary production but the resistance and resilience of an ecosystem are determined by the responsiveness and storage capacity of detritus-processing components. Contrasting CT and NT, one more disturbed (that is, plowed) than the other, provides an excellent opportunity for experimental study of the litter-soil "keystone" subsystem.

Plowing tends to bury plant residues, exposing them to a soil environment that enhances quick releases of inorganic nutrients and dissolved organic matter. In contrast, residues remain in larger pieces on the surface in the absence of plowing. Accordingly, decomposition is faster and nutrient mobility greater in CT than in NT systems (*15*). Nutrients are therefore more available and crop growth greater early in the season in CT. However, crop plants catch up in growth later in the season as nutrients are released by the slower decomposition pattern characteristic of NT systems. Yields at the end of the season have tended to be similar in NT and CT (*16*). In general, greater immobilization and slower release in NT means that nutrients are less likely to be lost from the crop field by leaching and runoff.

Tillage also affects microbial food chains. No-tillage management increases the importance of fungi relative to bacteria as primary decomposers, and hence as the resource base for the detrital food web. Fungi are more efficient decomposers of pieces of leaf, stem, and other coarse detritus than are bacteria. Plowing (CT), on the other hand, creates conditions favorable to bacteria-based food webs composed of disturbance-adapted organisms with high metabolic rates. The fungi-based and bacteria-based food chains are contrasted in Fig. 2, and some of the secondary consumers associated with each food chain are indicated. Thus, bacteria, protozoa, and other bacterivores are more abundant in CT systems, whereas fungi, microarthropods, other fungivores, and earthworms are more abundant in NT systems. There are seasonal variations in these patterns with the greatest contrast just after plowing in CT when pulses in both nutrients and microbial activity occur. Other contrasts in CT and NT are detailed elsewhere (*14–16*).

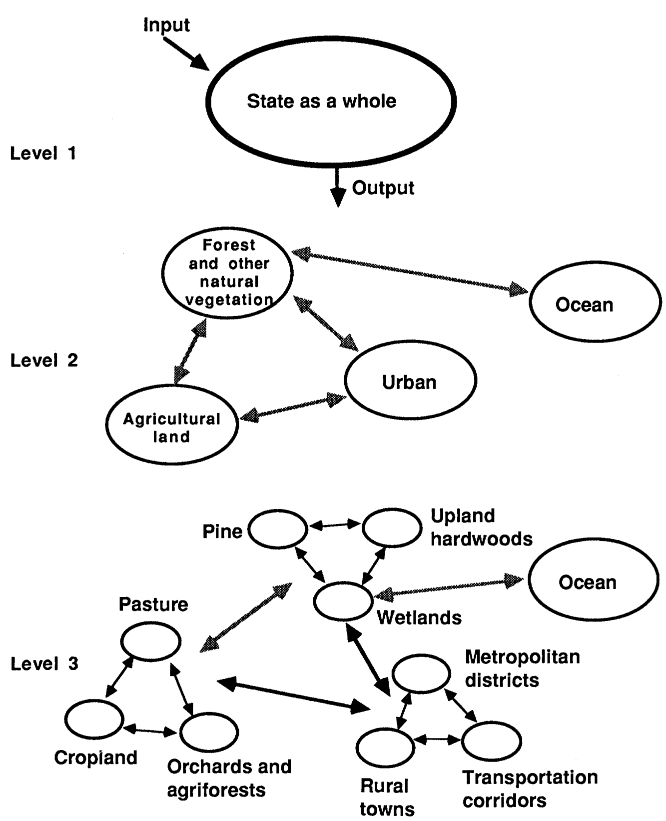

Fig. 3. A top-down schematic model of the Georgia landscape as a hierarchical system. Solid lines indicate strong, direct interaction; shaded lines, indirect, diffuse interaction. [Adapted from (*3*) with permission © 1987, American Institute of Biological Sciences]

The Georgia Landscape

A 2-year study of Georgia land and resource use provides an example of a top-down approach on the scale of the landscape (*17, 18*). First, the patterns of land use for the whole state and the four major physiographic regions as they have changed during the past 50 years were examined. Both spatial and temporal macrodimensions were documented. Then, major component parts, including ecosystem types (croplands, forestlands, wetlands, and urban districts), major resources (crops, water, and energy), and domestic and wild animal populations were analyzed in detail, often down to the county level. Next, calculations of net primary production and nonmarket values for the entire Georgia landscape were made. A hierarchical model for the Georgia study is shown in Fig. 3.

Changes in land use have been extensive in Georgia, reflecting the large-scale abandonment of marginal farmland (resulting in subsequent natural and artificial reforestation), improvement in productivity of prime farmland, increase in the domestic animal population, and rapid urbanization and human population growth in the northern part of the state. Over the past 50 years cropland has declined by about one-half and forestland has increased to 65% of total land area statewide. About 60% of Georgians now live in metropolitan districts, one-third in the nine-county Atlanta area.

Changes involve not only the proportion of land that is cropland, forest, or urban, but also spatial patterns such as patch size and complexity. In the 1930s the Georgia landscape was fragmented or "patchy," meaning that there were many very small patches of land for different uses. This fragmentation has declined during the past 50 years as individual tracts of forestland have increased in size and are now more connected. Crop fields have decreased in number but increased in size. Aerial photographs taken in the 1930s reveal that the rural piedmont landscape consisted of a matrix of cropland with numerous small patches of forests and other land uses. Today, forests make up the matrix and crop fields the patches. A question for the future is how will the competition between pine and hardwood forests turn out on the piedmont. Pine currently has a higher market value than hardwood but is replaced by hardwood in natural succession. Despite the efforts of foresters to maintain pine on the Georgia piedmont, the area occupied by hardwood is increasing (*19*). Both urbanization and suppression of fire favor the succession to hardwood.

Not only has the size of patches changed but also the complexity of patch shapes. For example, fractal dimensions calculated for patches as outlined from aerial photos have declined with time (*20*), indicating that tracts of major land uses have become more regular and less complex in shape. This change results from the tendency for increased human management of forests, croplands, and cities to "regularize" the contours of patches. The total amount of edge between all land uses decreased between 1930 and 1980, again supporting the fact that the Georgia landscape has become less fragmented. These basic changes in landscape patterns and the increase in urbanization have affected the distribution and abundance of passerine birds and game animals, with some species increasing, others decreasing (*17, 18*).

Resource Components

Trends in agriculture and in human and domestic animal populations are shown in Fig. 4. Overall, a sigmoid growth pattern is evident with the most rapid change occurring between 1950 and 1970, followed by a leveling off in the past decade. Agriculture provides a good example of this pattern. By converting bushels and pounds recorded in crop yield reports to calories, a picture of total crop output (including everything from watermelons to soybeans) can be presented. Twice as much food on half as much land is now produced on the Georgia landscape as compared to the 1930s, but at a high cost in fertilizer, pesticide, and water use. A 4-fold increase in yield has been accompanied by an 11-fold increase in nitrogen fertilizer (Fig. 4A).

The importance of the impact of domestic animals on the landscape is often overlooked. In Georgia, domestic animals in terms of population equivalents have increased over the past 50 years faster than the human population, so that the ratio of animals to humans has increased from 2:2 to 3:5 (Fig. 4B). Population equivalence was calculated on the basis of food consumption of cattle, pigs, sheep, and poultry on an annual basis as compared with human food consumption. For example, 73 broiler chickens are equivalent to one person, and a beef cow is equivalent to three persons in terms of food calories consumed. The calculation for 1983 indicated that the equivalent of the entire corn and soybean production of the state was used to feed chickens (broilers and laying hens).

The sigmoid growth form indicates diminishing returns and the need for a change in planning and management, not only for agriculture but for other resources as well. Water consumption statewide and water used for irrigation increased rapidly between 1955 and 1975 and then leveled off as water shortages in urban areas and drawdown of aquifers in rural areas began to cause concern. Dams have now been built on most of the suitable sites on Georgia rivers, so that building multipurpose mainstream dams becomes less appropriate in the future. The main need for the immediate future will be for small tributary reservoirs to provide water storage for urban areas in the piedmont where there are no large ground-water sources (aquifers). To maintain drinking water quality, real estate and other development on the watershed of such reservoirs must be restricted. To achieve such a goal a major shift in public policy is required, because development has generally been encouraged on the multipurpose reservoirs constructed in the past. Again this sort of about-face needs to be considered for all resources.

Productivity and Nonmarket Values Statewide

Data on yield of food and fiber harvested from croplands, pastures, and forests were converted to estimated net primary production (NPP) by means of appropriate conversion factors (harvest ratios, for example). The NPP for the whole Georgia landscape has more than doubled between 1935 and 1985, increasing from 2.5 to 6.4 metric tons of dry matter per hectare (*21*) (Fig. 5), a remarkable recovery when one considers what sociologist Gerald Johnson once called the South's "wasted land" of the 1930s (*22*). Both man and nature can take credit for this "greening of Georgia," because increase in agricultural yields, natural soil-building processes on eroded land, and improved silvicultural practices have contributed to increased landscape productivity. However, several world models suggested that the NPP of a region with the temperature-rainfall pattern of Georgia should be on the order of 16 to 18 metric tons per hectare (*23*). Apparently, the state has a way to go to repair the wasted land of the 1930s and reach its potential productivity.

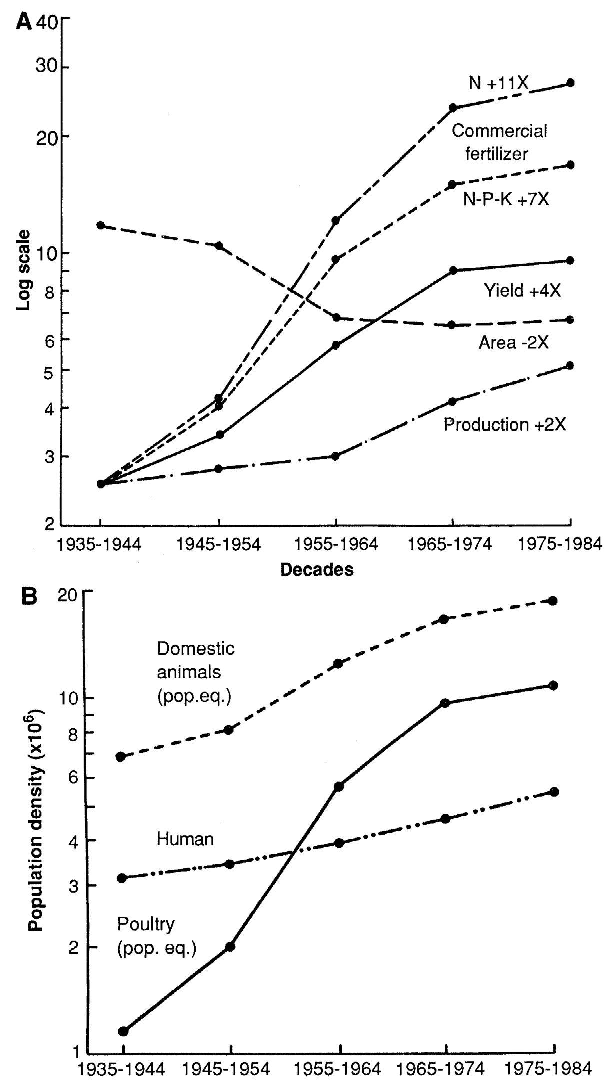

Fig. 4. (**A**) Fifty-year trends in crop area, crop yield, crop production, and fertilizer use in Georgia. (**B**) Fifty-year trends in human and domestic animal population density. [Adapted from (*18*)]

Landscapes produce many life-support and other services that are not incorporated into their market values. These nonmarket values may be quite large but must be measured indirectly. Wise and rational management of natural areas requires that these values be incorporated into the decision-making process. Methods for valuation of nonmarketed "goods and services of nature," such as those provided by wetlands, are currently receiving a lot of attention from both economists and ecologists (*24*).

Details of attempts to estimate the nonmarket value for the entire Georgia landscape in monetary terms are reported elsewhere (*25*). Both contingent valuation (an economic approach) and energy analysis (an ecological approach) were used; both approaches yielded similar estimates. The annual value of nonmarketed natural services in Georgia was conservatively estimated as $2.6 billion in 1982 dollars, which compares with an annual value of marketed agricultural products of $2.8 billion and a marketed timber production of $4.8 billion. If one assumes a constant stream of services into the indefinite future at a 4% discount rate, the total present value of nonmarketed goods and services would be $75.7 billion. This is an estimate of the worth of the state's life-support services provided mostly by the natural environment.

Natural areas are important not only for their nonmarketed life-support services and as buffers between urban-industrial and agricultural development but also for their recreational and scenic values, many of which also have a high market value. As yet there is no generally accepted formula for determining what portion of the landscape should be set aside to remain in a natural or seminatural condition. I suggest 20% as a reasonable goal. In Georgia, only 8% of the total land area is in parks, state and national forests, wildlife refuges, and green belts. For comparison, Florida has 14% of its landscape in public ownership, California, 46% (*26*). Natural area preservation is especially needed in the piedmont region where most Georgians live and where less than 2% is now in a "preserved" category.

Implications for Landscape Management

Fifty-year trends show how and to some extent why changes have occurred; they also suggest possible future trends and point out what needs to be done to prevent future problems, such as water shortages and a decline in water quality. Landscape ecological research that considers both temporal and spatial scales provides a basis for assessing change and for future planning and management. Land-use patterns integrate both natural- and human-developed environments. A great deal can be done at the state level, not only to improve quality of life within the state but also to reduce global stress on life-support systems.

On the basis of the results of the Georgia study (*17, 18*) as outlined here, the following recommendations have been made for growth management (that is, land-use planning) in Georgia, giving high priority to maintaining that environmental quality necessary to support future economic development. (i) A statewide effort is urgently needed to increase natural area preservation, especially in the piedmont region. (ii) Statewide legislation is needed for the protection of river corridors, freshwater wetlands, and water quality. (iii) In order to reduce air pollution, state and local governments should encourage power companies to invest in clean coal technology that is now economically feasible (*27*) by providing tax and other incentives. (iv) State and local governments should promote energy and water conservation and reduced input agriculture. (v) Educational campaigns and more emphasis on environmental education in colleges and universities are needed to increase public awareness of the nature and seriousness of nonpoint pollution and the value of

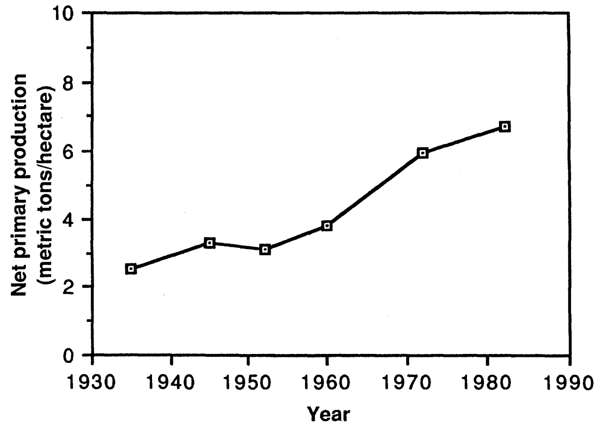

Fig. 5. Estimated NPP from 1935 to 1984 for the entire Georgia landscape (*21*).

and need for preserving the life-supporting environment. The last recommendation is extremely important because opinion surveys, conducted in the course of the studies, indicate that large segments of the public are not aware of the significance of changes in the Georgia landscape and do not perceive the need to take any action before there are actual shortages or crises.

Georgia is a good "mesocosm," that is, an area representative of a larger area (*28*), not only for the southeastern region of the United States but for the nation and much of the developed world as well. In some ways what has happened in 50 years in Georgia can be encouraging to developing countries. In the 1930s Georgia resembled a less-developed country. The state was largely agrarian, with low per capita income and educational levels; it was lacking in quality industry and hampered by a soil-destroying agriculture. In his masterwork, *Southern Regions of the United States*, my father, sociologist Howard W. Odum, documented in detail the condition of the region's human and natural resources in the 1930s, the reasons for the "chasm between the potentialities and actualities," and what needed to be done (*29*). In retrospect, much of H. W. Odum's prescription for curing the ills of the South has been carried out. Today, Georgia and many other southern states are well on their way to becoming "developed," with all the different problems that come with that status.

In the past, the land-grant state universities with their large investment in extension services have played major roles in improving agriculture and the quality of life throughout this country. However, because of the specialization and excessive fragmentation of departments and disciplines, I am not certain that the current state university is prepared for those future problems that will require a radically different approach from what worked in the past (the about-face discussed in this article). I would urge administrators to encourage the formation of interdisciplinary centers and institutes within their universities that take a more holistic approach to teaching, research, and service, especially regarding environmental concerns.

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Ergodic Theory, Randomness, and "Chaos"

D. S. Ornstein

Ergodic theory is the theory of the long-term statistical behavior of dynamical systems. The baker's transformation is an object of ergodic theory that provides a paradigm for the possibility of deterministic chaos. It can now be shown that this connection is more than an analogy and that at some level of abstraction a large number of systems governed by Newton's laws are the same as the baker's transformation. Going to this level of abstraction helps to organize the possible kinds of random behavior. The theory also gives new concrete results. For example, one can show that the same process could be produced by a mechanism governed by Newton's laws or by a mechanism governed by coin tossing. It also gives a statistical analog of structural stability.

Ergodic theory arose out of an attempt to understand the long-term statistical or probabilistic behavior of dynamical systems such as the motions of a billiard ball or the motions of the earth's atmosphere. The theory focused on certain mathematical objects called abstract dynamical systems or measure-preserving flows. The idea here is to abstract out the statistical properties and ignore other properties of the dynamical system. Thus two systems are considered the same when viewed as an abstract system (we call these isomorphic) if, after we ignore sets (or events) of probability zero, there is a one-to-one correspondence between the points in their phase spaces (see below) so that corresponding sets have the same probability and evolve in the same way (in other words, maintain the correspondences for all time) (*1*). If we preserved the topology instead of probabilities, we would be studying the qualitative theory of ordinary differential equations initiated by Poincaré.

Abstract dynamical systems are natural objects from the mathematical point of view, and they arise in many different contexts (even in areas as far afield as number theory); elucidating their structure is considered an important mathematical problem. Much of the work in ergodic theory has had little to do with its initial motivation, but recently certain problems, some of which had been unsolved for more than a decade, have been solved, and a group of results has been obtained that does relate to concrete systems such as the billiard system. These results, which I will refer to as isomorphism theory, center around a better understanding of a certain abstract dynamical system called the baker's transformation. This is a map of the unit square onto itself (Fig. 1). We first stretch the square, doubling its width and halving its height. We next stack the right half of the elongated rectangle above the left half (the shape is again a square). These two steps give the baker's transformation. If looked at properly the baker's transformation can serve as the mathematical model for coin tossing (this is easy to see), and in this sense is completely random while it is deterministic in the sense that every point moves in a definite way.

The baker's transformation is often used as a paradigm for explaining the possibility of deterministic chaos (*2, 3*), that is, systems that evolve according to Newton's laws but nevertheless appear to be random. In recent years people have become increasingly aware of the ubiquity of this phenomenon.

The author is professor of mathematics at Stanford University, Stanford, CA 94305.