THE ECOLOGICAL SCIENCES AND THE PUBLIC DOMAIN

WILLIAM M. LEWIS, JR.*

I. INTRODUCTION

The United States Bureau of Reclamation (the "Bureau"), builder of dams and irrigation works, seems an unlikely patron of ecological research, yet its growing expenditures on ecological studies may soon rival those of the National Science Foundation's Ecological Studies Program.[1] Ecological research accounts for only a small portion of the Bureau's overall budget,[2] but it is significant beyond its magnitude because it demonstrates new responsibilities for the Bureau. For example, the largest of the Bureau's ecological studies, accounting for about twelve million dollars per year, deals with the Colorado River in the Grand Canyon between Glen Canyon Dam and Lake Mead.[3] As operator of the Dam, the Bureau must account for the effect of the Dam's operations on environmental resources in the Grand Canyon. This responsibility raises technical questions, many of which can be answered only by ecological studies.

The Bureau is not alone in its need for ecological information. For example, the United States Army recently has supported a study of endangered tortoises in the Western Mojave Desert.[4] The Army has strong motivation for such a study because the tortoises, which are federally protected, may be affected by the Army's use of tanks.[5] Thus the Army, like the Bureau, supports ecological research even though its mission seems far removed from ecology.

There are many other examples of growing needs for ecological information. Even government agencies that have always dealt with biotic resources, thereby maintaining their connections to the ecological sciences, are now studying species and habitats that in the past have been unrecognized or unprotected and, for

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* Professor and Chair of the Department of Environmental, Population, and Organismic Biology, and Director of the Center for Limnology, University of Colorado.

1 . The Bureau of Reclamation spent about $15 million on ecological studies in 1993, but ecological studies are not separately tabulated in the Bureau's budget. Interview with David Wegner, Project Manager of Glen Canyon Environmental Studies, U.S. Bureau of Reclamation, in Flagstaff, Arizona (Nov. 1993). The current budget for the National Science Foundation's ("NSF's") Ecological Studies Program is $29.4 million; the total budget for environmental biology at NSF is $83 million, although this includes some areas that are not ecological. AMERICAN ASS'N FOR THE ADVANCEMENT OF SCI., RESEARCH AND DEVELOPMENT FY 1994, at 214 (1994).

2 . The budget of the Department of the Interior's Bureau of Reclamation is close to $850 million per year. OFFICE OF MGMT. AND BUDGET, BUDGET OF THE UNITED STATES GOVERNMENT: FISCAL YEAR 1994 app. at 693 (1993).

3 . COMMITTEE TO REVIEW THE GLEN CANYON ENVTL. STUDIES ET AL., SYMPOSIUM: COLORADO RIVER ECOLOGY AND DAM MANAGEMENT (1990). Cost of Glen Canyon Environmental Studies related in an interview with D. Wegner, *supra* note 1.

4 . D. DOAK ET AL., MODELING POPULATION VIABILITY FOR THE DESERT TORTOISE IN THE WESTERN MOJAVE DESERT: ECOLOGICAL APPLICATIONS (forthcoming 1994) (manuscript at 4, on file with author).

5 . *Id.* at 7.

these reasons, largely unstudied, as in the case cited above for the desert tortoise. Environmental legislation, such as the Endangered Species Act, and public opinion, as delivered for example through the public comment components of the National Environmental Policy Act, have set new requirements for the managers of public lands. The result is an increasing need for information that can be provided only by the ecological sciences.

Strong sociopolitical forces have affected the ecological sciences over the last thirty years. In fact, the affinity between the ecological sciences and management of public lands and public resources was probably stronger from 1930 to 1960 than from 1960 to the present. Reasons for estrangement between management and the ecological sciences after 1960 can be found in the public image of ecology as it developed through the mass media and through environmental legislation.

Before the environmental movement, the term "ecology" was not widely known. Subsequently, mass media reports on environmental problems began referring to ecology, but without making distinctions between scientific inquiry (ecology) and political viewpoints favoring protection of environmental resources (environmentalism). For many who first learned of ecology from a newspaper, this confusion has never been resolved.

Ecology is the scientific study of relationships between organisms and their environment;[6] it has no inherent political orientation.[7] Unfortunately, ecology in common usage often stands not only for science, but also for politics, behavior, and ideology. As a result, the true content of the ecological sciences has become obscure. This has dealt a serious blow to the usefulness of the ecological sciences in management of environmental resources. Who could blame a hydraulic engineer for doubting the utility of a discipline which works under a title that seems synonymous with karma?

Political struggles surrounding environmental legislation also have retarded application of the ecological sciences to management. Environmental politics did not grow out of ecology. Even so, the confusion between environmentalism as a political perspective and ecology as a source of information is so complete that the two are often considered interchangeable. One result of this confusion is that the United States has failed to support its environmental laws with appropriate research, even in the face of urgent needs for information.

The national criteria for dissolved oxygen, which is necessary for aquatic life, provide an example of the mismatch between environmental law and its scientific basis. The oxygen criteria,[8] which are one of many sets of criteria that de-

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6. ROBERT E. RICKLEFS, ECOLOGY 807 (3d ed. 1990).

7. Ecologists often have been among the first to comment on environmental problems, but this probably reflects scientific foresight comparable in many ways to that of physicists who expressed early concerns over the dangers of nuclear energy. A good discussion is given in ROBERT P. MCINTOSH, THE BACKGROUND OF ECOLOGY: CONCEPT AND THEORY 292-323 (1985).

8. OFFICE OF WATER REG. AND STANDARDS, ENVIRONMENTAL PROTECTION AGENCY, PUB. NO. 440/5-86/003, AMBIENT WATER QUALITY CRITERIA FOR DISSOLVED OXYGEN (1986).

rive from the Clean Water Act,[9] are used by the United States Environmental Protection Agency ("EPA") and the states in setting discharge allowances for approximately 15,000 municipal discharges,[10] as well as large numbers of industrial discharges. Despite their importance, the oxygen criteria are based on solid information for only about a dozen of the 800 species of freshwater fishes that occur in the United States.[11] Furthermore, the pool of information supporting the criteria has changed very little in the last twenty years. It is irrational for such important regulations as these to be founded on fragments of information.

The United States should have shown a great surge in basic ecological research in the wake of environmental legislation. The surge actually has been very modest, and insufficient to meet the needs that follow directly from environmental legislation. Given the confusion between ecology and environmentalism, federal investments in the ecological sciences probably have been viewed as subsidies to environmental politics. This is unfortunate, given that environmental legislation cannot be implemented rationally without ecological insight.

Increasing amounts of environmental legislation and regulation raise some basic questions for managers of public lands. First, what is ecology and how did it develop? Second, to what extent can ecology give answers to practical questions of the type that arise in resource management? Finally, is ecological knowledge now being used to its best advantage in the management of public lands? These three questions are the subject of this article.

II. Roots and Branches of the Ecological Sciences

Most of the problems that occupy the attention of ecologists can be grouped under four headings: (1) adaptations of organisms, (2) abundance and distribution of organisms, (3) structure and composition of multispecies associations, and (4) ecosystem structure and function. Reflecting a similar progression of scale and complexity, ecological studies also can be classified according to a hierarchy which extends from individual organisms to populations, and then to mixed species communities, ecosystems, landscapes, biomes, and the biosphere.[12] The methods of choice vary along the spectrum; the organismic ecologist frequently proceeds by controlled experiments, whereas the ecosystem scientist must rely more on uncontrolled experiments, modeling, and measurements made in the natural setting.

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9. Federal Water Pollution Control Act of 1972, 33 U.S.C. § 1251 (1988 & Supp. 1992).
10. FRITS VAN DER LEEDEN ET AL., THE WATER ENCYCLOPEDIA 540 (2d ed. 1990).
11. *See* OFFICE OF WATER REG. AND STANDARDS, *supra* note 8.
12. ROBERT L. SMITH, ECOLOGY AND FIELD BIOLOGY 1-27 (2d ed. 1974).

A. *Adaptation*

Any genetically-based change in a population is an example of evolution.[13] Evolution thus encompasses minute adjustments of populations as well as the derivation of entirely new species. Until 1859, when The Origin of Species[14] was published, the mechanism of evolution was not understood. The concept of evolution, and particularly the origin and diversification of all stocks of living organisms out of pre-existing stocks, permeated The Origin of Species and was the main cause of its immediate popularity (the first printing was sold-out on the day of its release).[15] However, the concept of evolution was not new; it had appeared in the work of Lamarck fifty years before, and can be found in more diffuse form even earlier.[16] Darwin's contribution was to legitimize evolution scientifically by showing its mechanism, which he called "natural selection."[17]

Natural selection, which is ecology's first law, dictates that differential reproductive success constantly adjusts the physical, physiological, and behavioral characteristics of living populations to the demands of their environment. In this sense, all populations are evolving, and all organisms are a template of their environment.

A corollary of the law of natural selection is that any directional change in the environment will force a population's genetic template out of focus. If the change is gradual, as in the case of some past climatic changes, a population may become refocused by the development of a new balance of characteristics through natural selection. Alternatively, the population may become extinct or it may be redistributed to more favorable locations.

Industrial societies cause environmental change that is both rapid and drastic, and in doing so induce disequilibrium between the genetic templates of populations and their living conditions. The result is sweeping change in the relative abundance and distribution of species throughout the world and an alarming rate of species extinction.[18]

In the United States, two major pieces of legislation are based directly, albeit unintentionally, on the law of natural selection. The first of these is the Endangered Species Act of 1973 ("ESA").[19] One premise of the ESA is that a species cannot be expected to persist if its environmental matrix is reduced or changed.[20] It follows that protection of the environmental matrix is essential

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13. MONROE W. STRICKBERGER, EVOLUTION 418 (1990).

14. CHARLES R. DARWIN, THE ORIGIN OF SPECIES BY MEANS OF NATURAL SELECTION; OR, THE PRESERVATION OF FAVORED RACES IN THE STRUGGLE FOR LIFE (London, John Murray 1859).

15. ADRIAN DESMOND & JAMES MOORE, DARWIN 477 (1991).

16. Lamarck's work as well as earlier works dealing with organic evolution are described in E. MAYR, EVOLUTION AND THE DIVERSITY OF LIFE (1976).

17. *See* DARWIN, *supra* note 14, *passim*. The term "natural selection" first appears on the title page of the book.

18. EDWARD O. WILSON, THE DIVERSITY OF LIFE 243-80 (1992).

19. 16 U.S.C. § 1533 (1988).

20. *See, e.g., id.* § 1533(b)(2) ("The Secretary shall designate critical habitat . . . .").

for protection of the species. The Clean Water Act also is based strongly on the law of natural selection. Some of the most expensive consequences of this legislation derive from the protection of aquatic life through restrictions on the discharge of waste.[21] The Clean Water Act, as applied through criteria documents such as the one for dissolved oxygen,[22] requires that organisms not be impaired in their growth or abundance by wastewater discharge. This is much the same as requiring that surface waters not vary in their chemical characteristics beyond the range of natural variation to which organisms are adapted. The degree of societal adjustment inherent in this requirement is astonishing. For example, the rainbow trout tolerates about twenty μg/l of unionized ammonia,[23] whereas the waste stream from an ordinary municipal treatment plant might contain as much as 2,000 μg/l of unionized ammonia.[24] The gap between the two concentrations can be closed only by specialized, expensive treatment of the waste prior to discharge.[25]

Application of the law of natural selection could be much more extensive than it is now. Aside from the ESA, the tolerance of organisms in terrestrial environments for anthropogenic change is recognized primarily through restrictions on the use of toxic exotic substances such as herbicides and pesticides, but even these regulations have more to do with concerns over human health than with protection of the rest of the biota.[26] The physical attributes of most environmental systems, with the notable exception of wetlands,[27] are essentially unprotected. This is especially ironic for aquatic systems, where chemical protection is elaborate. For example, a discharger cannot chemically impair the growth of fish in a stream by even a few percentage points, but in many states a diverter can own the right to deprive them entirely of water.[28]

The law of natural selection dictates that societies have the choice of deferring to the tolerances of organisms for all kinds of anthropogenic change or of accepting continued decline in biotic diversity.

21. GEORGE TCHOBANOGLOUS & FRANKLIN L. BURTON, WASTEWATER ENGINEERING: TREATMENT, DISPOSAL, AND REUSE 694-710 (3d ed. 1991).

22. *See* AMBIENT WATER QUALITY CRITERIA FOR DISSOLVED OXYGEN, *supra* note 8.

23. OFFICE OF WATER REG. AND STANDARDS, ENVIRONMENTAL PROTECTION AGENCY, PUB. NO. 440/5-85/001, AMBIENT WATER QUALITY CRITERIA FOR AMMONIA 10-12 (1985).

24. *See* TCHOBANOGLOUS & BURTON, *supra* note 21, at 109.

25. *Id.* at 693-763.

26. The key reference for standards related to herbicides, pesticides, and toxic organic substances generally is the so-called "Gold Book," which focuses primarily on concentration limits for the protection of human health. OFFICE OF WATER REG. AND STANDARDS, ENVIRONMENTAL PROTECTION AGENCY, PUB. NO. 440/5-86/001, QUALITY CRITERIA FOR WATER (1986).

27. WILLIAM GOLDFARB, WATER LAW 142-48 (1988).

28. DAVID H. GETCHES ET AL., CONTROLLING WATER USE: THE UNFINISHED BUSINESS OF WATER QUALITY PROTECTION 91-92 (1991).

B. *Population Ecology*

A large branch of ecology is dedicated to the analysis of populations, which can be defined as groups of interbreeding organisms of the same species.[29] The responses of populations to anthropogenic change frequently cannot be anticipated from laboratory tolerance tests. In nature, populations are affected by multiple, interacting stresses that vary through space and time. For this reason, there is a consistent element of field study in population ecology.

A few of the central ideas of the population ecologist allow some illustration of the importance of population ecology to the management of biotic resources.[30] The rate of growth (r) of a population is the difference between its birth and death rates ($r = b-d$).[31] Populations have inherent maximum growth rates (r_{max}) that occur when the upper limits of reproductive capacity are combined with low rates of mortality.[32] The value of r_{max} can be used to forecast the maximum expected productivity of a biotic resource, and the ratio of r (observed rate of increase) to r_{max} (maximum possible rate of increase) over time can show whether a population is being consistently suppressed.[33] Because birth rates and death rates affect r, the first step in a population analysis is identification of factors influencing these two rates. Such an analysis often reveals bottlenecks that thwart population growth. Examples are scarcity of a particular habitat feature or high mortality at a specific life stage.[34]

Populations that grow steadily at a fixed rate (*e.g.*, r_{max}) will show exponential increase in size (they will increase according to the principle of compound interest). Of course, populations cannot grow indefinitely; they ultimately reach a saturation limit, called carrying capacity (K), for a given environment.[35] As populations approach K, their rate of growth decreases.[36] The carrying capacity concept is of great practical value because the effects of anthropogenic change can be measured as a suppression of K for any given species or for combinations of species.

The principles of population ecology have been used for decades in management of fish and wildlife through regulation of harvest rates and protection of critical habitat.[37] The same concepts also apply to timber production and even to row crops. However, the concepts of population ecology have been ap-

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29. RICKLEFS, *supra* note 6, at 279.
30. A clear presentation of these and related concepts can be found in G. EVELYN HUTCHINSON, AN INTRODUCTION TO POPULATION ECOLOGY 1-5 (1978); *see also* RICKLEFS, *supra* note 6, at 302-24.
31. RICKLEFS, *supra* note 6, at 323.
32. C.J. KREBS, ECOLOGY 184 (3d ed. 1985).
33. *Id.*
34. *Id.*
35. *Id.* at 215.
36. *Id.*
37. *See* SMITH, *supra* note 12, at 410.

plied only sparingly to the protection of species that lack value for commerce or sport. The broadest legal application is probably through the ESA,[38] which in effect requires that K be maintained for endangered species by protection of critical habitat; however, endangered species make up only a small fraction of the biota. Population ecology provides much unexploited potential for evaluation and protection of organisms that are neither endangered nor of commercial value.

C. *Multispecies Associations*

The ecology of multispecies associations, or community ecology, developed initially from the study of plant communities.[39] Community ecology deals primarily with two questions: (1) What controls the number of species (species diversity)?[40] and (2) How does the species mix develop through biotic succession for a given sort of physical and chemical environment?

The diversity question has recently taken on explicit practical overtones with the growth of public concern over widespread simplification of biotic communities. It is a principle of community ecology that highly stressed communities are simple, i.e., they show low diversity.[41] Hypersaline environments provide one kind of natural example, as shown by the Great Salt Lake. The only two kinds of macroinvertebrates to reach abundance in the Great Salt Lake are brine shrimp (Artemia) and larvae of the brine fly (Ephydra).[42] This contrasts markedly with the diversity of faunas in freshwater or moderately saline lakes, which support dozens or hundreds of species. The chemical challenge of the Great Salt Lake's hypersaline waters is so extreme that few invertebrates have become adapted to it. Similarly, strong anthropogenic stress typically simplifies biotic communities.[43]

Anthropogenic stress often can be classified as disturbance. In fact, the central principle of agriculture is drastic and repeated disturbance in the form of plowing and cultivation as a means of preventing the development of diversity, which is explicitly unwanted on croplands.

Disturbance is not inherently unnatural. In fact, the species of a community are often held in balance with each other partly by natural disturbances that repeatedly shift the advantage from one species to another, thus preventing any given species from capturing all of the resources.[44] In this way, disturbance may

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38. 16 U.S.C. § 1533; *see supra* notes 19-20.

39. M.J. BARBOUR ET AL., TERRESTRIAL PLANT ECOLOGY (2d ed. 1987).

40. Species diversity involves not only the number of species, but also the equitability in abundance of species. For example, a community containing ten species of equal abundance is considered to be more diverse than a community containing ten species of which one is abundant and nine are rare. *See* ROBERT H. WHITTAKER, COMMUNITIES AND ECOSYSTEMS (2d ed. 1975).

41. *See* RICKLEFS, *supra* note 6, at 750.

42. Frederick J. Post, *The Microbial Ecology of the Great Salt Lake*, 3 MICROBIAL ECOLOGY 143, 149 (1977).

43. ROBERT G. WETZEL, LIMNOLOGY 197 (1983).

44. RICKLEFS, *supra* note 6, at 766.

promote as well as suppress diversity.[45] Community ecology offers the means for predicting changes in diversity and species composition in response to varying degrees and kinds of anthropogenic disturbance.

Maintenance of biotic diversity is a potential goal for management of public lands. Had diversity been valued in the past, management practices would have developed differently. For example, fire suppression, which can reduce diversity in some plant communities that are dependent upon frequent renewal by fire, has in the past been a principle for management of United States forests.[46] Similarly, overgrazing, a cause of biotic degradation on rangeland,[47] might have been controlled by assignment of significant value to biotic diversity. The public range manager of the future might refer to charts or tables showing the relationship between abundance of cattle per acre and plant species diversity for a given type of range. This will not happen, of course, unless biotic diversity is an objective of management.

D. *Ecosystem Science*

The most inclusive branch of ecology is ecosystem science, which is the integrated study of large environmental units such as forests, watersheds, or lakes.[48] Ecosystem science in some ways is the least established of the main branches of ecology. This is partly because ecosystem studies are more expensive than other kinds of ecological studies and partly because many of the tools and methods that make ecosystem studies so feasible today have been available for only a few decades. Ecosystem science, which draws heavily on the other ecological sciences, deserves special attention because it is the most suitable foundation for management of public lands.

III. ECOSYSTEM SCIENCE: A BASIS FOR MANAGEMENT OF PUBLIC LANDS

A. *Origins of the Ecosystem Concept*

The ecosystem concept came to maturity in an eleven-page essay on lakes by S.A. Forbes published in 1887.[49] Forbes saw lakes as super-organisms, i.e., as

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45. Diversity is often maximum at intermediate levels of disturbance. This concept is referred to as the "intermediate disturbance hypothesis," first described explicitly by Joseph H. Connell, *Diversity in Tropical Rain Forests and Coral Reefs*, 199 SCIENCE 1302, 1303-06 (1978).

46. *See generally* STEVEN J. PYNE, FIRE IN AMERICA: A CULTURAL HISTORY OF WILD LAND AND RURAL FIRE (1982); C. CHANDLER ET AL., 1 FIRE AND FORESTRY: FOREST FIRE BEHAVIOR AND EFFECTS (1983).

47. CHARLES F. WILKINSON, CROSSING THE NEXT MERIDIAN: LAND, WATER AND THE FUTURE OF THE WEST 75-113 (1993).

48. JOHN D. ABER & J.M. MELILLO, TERRESTRIAL ECOSYSTEMS 1-14 (1991).

49. S.A. Forbes, *The Lake as a Microcosm*, BULL. SCI. ASS'N PEORIA, ILL. 77-87 (1887). The antecedents of ecosystem science can be found in a number of other places as well. Some ecologists attribute less significance to the work of Forbes than would be indicated here. *See also* JOEL B. HAGEN, AN ENTANGLED BANK: THE ORIGINS OF ECOSYSTEM ECOLOGY 7-11 (1985); MCINTOSH, *supra* note 7.

complete functional units of nature rather than loose collections of living and nonliving objects.[50] Because integrated systems typically have properties that cannot be predicted from their parts, it follows that the study of ecosystems is useful and necessary to a well-rounded understanding of nature.

Forbes' contribution extended well beyond mere recognition of the ecosystem. In fact his main contribution, which in retrospect was remarkably prescient, was to describe the ways in which ecosystems can be analyzed. He pointed out that ecosystems have an aggregate metabolism, which he divided into cycles of building up and breaking down.[51] In modern terms, these cycles would be labeled as anabolism and catabolism or production and decomposition. Forbes also observed that the organisms of an ecosystem interact in a highly organized way through competition and food webs that set constraints on the abundance of individual species.[52] He noted that organisms are not distributed randomly within the system, but rather according to physical and chemical gradients in the environment.[53] He emphasized that the circulation of matter, which now would be called the study of element cycling, is a universal way of measuring the functional characteristics of ecosystems.[54]

The term "ecosystem" was not used by Forbes. It was introduced by A.G. Tansley, a British plant ecologist, in 1935.[55] Forbes' lake ecosystem had clear boundaries, but Tansley drew similar ideas into a more general form applicable to any bit of landscape that shows functional integration, even in the absence of clear boundaries. This made the concept more useful. Even so, the ecosystem concept cannot be applied over regions so large or spatially dissected that they are not functionally integrated. For example, one would not refer to the Rocky Mountains as an ecosystem. Such large units typically consist of many ecosystems and may be referred to as landscapes. Regions too large to be functionally integrated, but showing similar complexes of dominant organisms, are sometimes called biomes,[56] and the life zone of the entire Earth makes up the biosphere.[57] Some of the concepts outlined by Forbes, particularly the concepts of system metabolism (energy flow) and element cycling, have been the central organizing principles for studies of biomes and of the biosphere.

B. *Better Measurements*

The capabilities of ecosystem science have been greatly magnified by technological change. The measurement of mass flux, which is the means by which the

50. Forbes, *supra* note 49, at 77.
51. *Id.*
52. *Id.* at 87.
53. *Id.* at 81-84.
54. *Id.*
55. A.G. Tansley, *The Use and Abuse of Vegetational Concepts and Terms*, 16 ECOLOGY 284-307 (1935).
56. SMITH, *supra* note 12, at 256.
57. *Id.* at 18.

element cycles of ecosystems can be studied, has changed from difficult to routine with the invention of instruments that can measure the amounts of substances found in ecosystems or in the air and water as they move through ecosystems.[58] This new capability has brought ecosystem scientists into closer contact with management. For example, terrestrial ecosystems possess finite inventories of critical plant nutrients such as nitrogen, phosphorus, and potassium.[59] In natural systems, the inventories of these elements accumulate over thousands of years.[60] Management practices that lead to large losses of critical nutrients are potentially harmful to the long-term integrity of ecosystems. Two ecosystem scientists created a sensation when they demonstrated that clearcutting of an experimental forest in New Hampshire was accompanied by massive losses of inorganic nitrogen, a key element for plant growth.[61] Their study showed that conservation of nutrient inventories is a critical aspect of timber management.[62]

Energy flux, the index of ecosystem metabolism, can also be measured. Quantification of gas exchange or of the rate of uptake of labeled substances can be used in calculating production and decomposition rates for entire ecosystems or for ecosystem components such as primary producers (plants), primary consumers (herbivores), and secondary consumers (carnivores).[63] Analysis of production at various levels of the food web is the first step in the diagnosis of bottlenecks that interfere with the transmission of energy from lower to higher levels of the food web. Management may either increase or decrease ecosystem production and may influence distribution of production among ecosystem components. For these reasons, production is a useful index for ecosystem management.

Technology has also helped ecosystem science break through the complexity of multispecies interactions in natural and managed ecosystems. For example, the use of stable isotopes as natural tracers in aquatic and terrestrial ecosystems has allowed food webs to be traced without detailed studies of individual species.[64] Such technical improvements have increased the usefulness of ecosystem science.

C. *The Digital Computer*

For about a decade beginning in the middle of the 1960's, ecosystem science was seduced by electronics. The attraction between ecosystem science and computers is powerful because ecosystem analysis deals with amounts of information

58. *See generally* STEWART E. ALLEN, CHEMICAL ANALYSIS OF ECOLOGICAL MATERIALS (2d ed. 1989).
59. *See generally* ABER & MELILLO, *supra* note 48.
60. *Id.* at 119-38.
61. *See* GENE E. LIKENS ET AL., BIOGEOCHEMISTRY OF A FORESTED ECOSYSTEM (1977).
62. *Id.* at 114-15.
63. ROBERT G. WETZEL & GENE E. LIKENS, LIMNOLOGICAL ANALYSES (2d ed. 1991).
64. Bruce J. Peterson & Brian Fry, *Stable Isotopes in Ecosystem Studies*, 18 ANN. REV. ECOL. SYS. 293 (1987).

so large that even simple tabulation of the data is slow and awkward without computers. For this reason, ecosystem science embraced the computer enthusiastically, but in doing so developed unrealistic expectations for ecosystem analysis by computer modeling.[65]

Had it been feasible, representation of ecosystems on computers through the use of large sets of equations would have made a very different ecosystem science from the one that exists today. Effects of such management practices as the addition of fertilizer or removal of cattle could have been predicted through a complex algorithm that would estimate readjustments in production, species distributions, and other characteristics of the system. In retrospect, it is easy to find several fallacies in such high ambitions for computer modeling of ecosystems. These fallacies are instructive not only for historical reasons, but also because they define some limits of expectation for ecosystem science in the future.

When two estimates are combined mathematically, as is necessary to predict their interaction, their variances are also combined. Because ecosystems consist of dozens of sets of interactions that must be combined to produce equations representing natural processes, uncertainty of estimation is propagated along with the calculations. The consequence for large, integrative models is excessive uncertainty. Various techniques can be used to suppress variance, but they are unlikely to be successful in containing it within realistic bounds in complex models involving large numbers of coupled equations.

Another problem is unknown interactions and components. It is not unusual for field studies on even well-known ecosystems to turn up insights that require major revision of the functional picture of the ecosystem,[66] just as the mental image of a personal acquaintance still can be evolving after twenty years of contact. It is impossible to know most ecosystems well enough to represent them fully as sets of equations.

A final difficulty lies in the qualitative change of ecosystems as they are disturbed. Equations that perform reasonably well in predicting repetitive responses may fail utterly if the ecosystem assumes an altered state.

It is unfortunate that modeling fell into some disrepute following the overextension of its legitimate possibilities. Modeling remains a central tool for ecosystem analysis and can provide accurate forecasts within modest boundaries. Models are particularly useful for organizing massive data sets, producing estimates of mass transport or energy flow, and forecasting the interaction of closely coupled variables that have been well studied.

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65. *See* HAGEN, *supra* note 49; MCINTOSH, *supra* note 7, at 240-41.

66. An example is the discovery that tree harvesting leads to large losses of inorganic nitrogen. *See* LIKENS ET AL., *supra* note 61.

D. *Capabilities of Ecosystem Science*

The present capabilities of ecosystem science are quite substantial and are essential for rational management of public lands. However, they do not now and never will approach a deterministic pinnacle comparable to predictions of the attraction of two bodies in space, as shown by Newton's law of universal gravitation.[67] Predictions about ecosystems must be framed in probabilistic terms.

The potential of ecosystem science is most easily shown by analogy with more familiar disciplines that have similar inherent characteristics. For example, atmospheric science and economics both deal with complex integrated systems, are sciences of immense practical importance, and both show their value primarily through broad-brush analysis, illustration of mechanisms, and short-term predictions rather than long-term, detailed forecasts. The same will be true of ecosystem science.

IV. BARRIERS AND IMPEDIMENTS

Large management agencies may be shifting their frame of reference from a multiple-use concept to an ecosystem concept.[68] One logical corollary of an ecosystem basis for management is that ecosystem integrity, which involves retention of the ecosystem's main functional characteristics, will be a significant value in management. A second corollary is that all natural attributes of the system will be maintained unless there is some rational justification for changing them and any irreversible change is assigned a realistic cost.

While there is reason to be enthusiastic about the possibilities for ecosystem-based management, there are at least six major impediments to its development:

(1) Subsidized resource extraction. Subsidies may be good, bad, or indifferent for society; ecology has nothing to say about this. However, the root of unprofitability for many subsidized management practices is that strong ecological forces operate against them and can be offset only by subsidy. An ecosystem basis for management probably will work against subsidies, and this will raise objections to ecosystem management.

(2) Valuation systems. Ecosystem-based management cannot succeed without valuation systems that assign weight to maintenance of basic ecosystem functions. With present multiple use systems for management, the dominant use is often the only factor considered when major decisions are made. For example, maintenance of biodiversity, ecosystem integrity, or aesthetic and recreational values has had little effect on the management of the public range, where the dominant use has been grazing.[69]

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67. GALE E. CHRISTIANSON, IN THE PRESENCE OF THE CREATOR 307-12 (1984).
68. Robert B. Keiter, *Taking Account of the Ecosystem on the Public Domain: Law and Ecology in the Greater Yellowstone Region*, 60 U. COLO. L. REV. 923, 1006-07 (1989).
69. WILKINSON, *supra* note 47, at 90-113.

This is in effect a binary decision system. If a given practice is beneficial to the main objective, it is favored; otherwise, it is not. Ecosystem-based management cannot succeed without the use of graded valuation systems that assign weight to the primary uses, the secondary uses, and the maintenance of basic ecosystem functions. The scale of values need not be the same for all sites; however, it should be explicit and under continual discussion and modification in response to economic forces, public preferences, and new knowledge about ecosystems and ecosystem management. It would make sense for recreational values to be incorporated into such a system, as well as the public preference or "nonuse values."

Resistance to such policies would probably come from both sides of the political spectrum.[70] Managers of timber, livestock, and irrigation may see their effectiveness undermined by new constraints. Others who would like to see public lands valued more highly for aesthetic or recreational appeal may not wish to weigh these uses against the value of commodities. The resolution of this tension will be irrational in the absence of management systems that attach explicit values to all uses.

(3) Interagency conflict. Agencies are associated with specific resources and not with ecosystems.[71] For ecosystem management to work, cooperation among agencies would need to be considerably better than it is now.

(4) Ecosystem expertise. If the ecosystem is the basis for management, then ecosystem science becomes the foundation for management. At the present time, the pace of ecosystem science in the United States and the supply lines for ecosystem expertise are too weak to satisfy the demand that public agencies could legitimately place on them. A substantial increase in the pace of ecosystem studies, with particular attention to practical problems associated with the management of public lands, is needed in the United States.

(5) Administrative motivation. Managers must be directed to use the ecosystem as a basis for management because this will involve a reduction in the efficiency of more traditional management activities.

(6) Legally binding ecological nonsense. The managers of public lands have considerable latitude to change their practices. However, even powerful agencies are constrained by law which is sometimes ecologically nonsensical. An example is the doctrine of prior appropriation for the establishment of water rights in the western states.[72] As presently applied, this doctrine amounts to a legal requirement for the impairment of water quality, the arbitrary de-watering of aquatic ecosystems, and the continuation of irrigation where it may make sense neither ecologically nor economically. The doctrine is directly antithetical to an ecosystem management approach.

70. *Id.*
71. *See* Keiter, *supra* note 68.
72. *See* GETCHES ET AL., *supra* note 28, at 89-92.

Legal reform could be an important step in promoting ecologically realistic management practices. Given that present interest in ecosystem management is motivated by a deep-seated change in public values, it is essential to re-examine the laws and regulations that affect the management of public resources. Given the six difficulties that stand in the way of ecosystem-based management, there are several possible futures. A pessimistic view would be that the change from multiple use to ecosystem management will be primarily nomenclatural. This seems most probable in the absence of administrative or legislative reform, because management agencies are unlikely to tamper with their fundamental policies in the absence of external direction to do so. A second possibility is evolution of management, but only as is necessary to reflect more fully the spirit of present environmental legislation. Some of this evolution is now in progress. A third possibility is a fundamental change in the management of public lands centered around ecosystem management principles. This seems likely only through new legislation that specifically redefines the responsibilities of agencies, such as legislation that redirects the management of public lands.

V. CONCLUSION

Following years of mutual aversion, ecologists and land managers are now making better contact with each other. The ecological sciences, particularly ecosystem science in the future should be a part of the standard repertoire of all management agencies. This would increase greatly the comfort of agencies in responding to environmental legislation and would provide a reliable foundation for the ecosystem approach to the management of public lands. The ecological sciences provide tools for assessing nature's tolerances. In an era when preservation of ecosystem integrity and protection of biotic diversity are joining more traditional priorities, the ecological sciences will prove indispensable to the management of public lands.