SUMMARY REPORT

MANAGEMENT-SCALE ECOSYSTEM RESEARCH

FINDINGS AND RECOMMENDATIONS

August 29, 1997

Daniel B. Botkin, Patrick Megonigal, and R. Neil Sampson

ACKNOWLEDGMENTS

This report summarizes the results of a workshop sponsored by the Strategic Environmental Research and Development Program (SERDP), Department of Defense (DoD), which consisted of 18 active participants and more than 30 advisors and observers, whose names appear below. Much of this report is the result of discussions held by these people during the workshop and I am appreciative of their contributions. I would also like to thank SERDP, HydroGeoLogic, Inc., and Labat Anderson, Inc., sponsors of the workshop.

This report builds on a background "white paper" prepared with coauthors R. Neil Sampson, the Sampson Group, Alexandria, Virginia, and Patrick Megonigal, George Mason University. In particular, Neil Sampson contributed much of the discussion of ecosystem management and Patrick Megonigal led development of the background paper's material on biogeochemical cycles. I am much indebted and appreciative of the contributions of all the participants and coauthors of the background papers. I wish to thank all of those who participated and contributed greatly to the report. However, the present report is my summary of the discussion and therefore any errors or misunderstandings of the workshop discussions are mine.

Daniel B. Botkin
President, The Center for the Study of the Environment
Santa Barbara, CA 93105

Professor of Biology
George Mason University
Fairfax, VA 22030

List of Participants

Femi Ayorinde
SERDP

Gary Belew
HQ Fort Carson

Rosina Bierbaum
Office Science & Tech./
Exec. Off. Pres

Alan Bivings
U.S. Army Forces Command
(FORSCOM)

Peter Boice
Dep. Under Secy. Defense
for Env. Security

Daniel B. Botkin
George Mason University

Robert Boyd
Off. Env. & Life Sci., Defense
Dir. Res & Engineering/SERDP

Richard Carpenter
SERDP Scientific Adv. Brd

Norman Christensen
Duke University

Kenneth Cummins
South Florida Water Mgmt. District

Roger Dahlman
Off. Energy Research
HQ DOE

Virginia Dale
ORNL; SERDP; ESA

Ron Dow
Naval Air Weapons Station,
Pt. Magu, Calif.

Thomas Dunne
University of Calif., Santa Barbara

Gary Evans
National Resources Institute

Lorne Everett
Geraghty & Miller, Santa Barbara

Penny Firth
Div. Env. Biology/National
Science Foundation

Paul Gilman
National Research Council

Mark Harwell
University of Miami

John Hobbie
Ecosystems Center, Woods
Hole

Bob Holst
SERDP

Jeff Holland
U.S. Army Corps of Engineers
Waterways Experiment Station

Melvin Jackson
Range Control Comd./SERDP

Peter Jutro
U.S. EPA

Pete Kirby
U.S. Army Corps of Engineers
Waterways Experiment Station

Nick Lancaster
Desert Research Institute

Michelle Leslie
Nature Conservancy

Claudia McMurray
Nat. Fish & Wildlife
Foundation

Christopher Margules
CSIRO Div. of Wildlife
Ecology

James Morris
University of South Carolina

Dave Mouat
Nat. Health & Env.
Effects Res. Lab./EPA

Lee Mulkay
U.S. EPA

Maury Nyquist
U.S. Geological Survey/
BRD

Donald Pryor
Office Science & Tech./
Exec. Off. Pres

James F. Reynolds
Duke University

R. Neil Sampson
American Forests

Timothy Seastedt
Inst. Arctic/Alpine Res.
U of Colorado

Robert Shaw
Colorado State Univ.
CEMML

Michael Slimack
Nat. Ctr. Env. Assess.

Bradley Smith
SERDP

Matthew Sobel
State University of N.Y.
Stony Brook

Whitney Tilt
Nat. Fish & Wildlife
SERDP Sci. Adv. Brd.

Walter Weber
Dept. Civil & Env. Eng.
U of Michigan

David C. White
University of Tenn./Oak
Ridge
National Lab

Gordon Wood
SERDP

Thanks also go to the support staff at the workshop, namely, Jan Kool, John Ruprik, Lori Labat, Mike Hathaway, and Patrick Megonigal and CSE staff members Susan Day, Joan Melcher, Elizabeth Mook, and Karen Redden.

I. EXECUTIVE SUMMARY: MANAGEMENT-SCALE ECOSYSTEM RESEARCH

This document presents the results of a workshop sponsored by the Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP), called The Management-Scale Ecosystem Research Workshop held June 2 through 5, 1997, at Airlie House, Virginia. The workshop was organized in response to a requirement by the Deputy Under Secretary of Defense for Environmental Security to ensure that ecosystem management becomes the basis for future management of all DoD lands and waters. The working hypothesis of the workshop was:

(1) it is possible to do ecosystem scale research on military lands while operations are ongoing;

(2) that this research would be supportive of specific military missions and to overall military mission readiness;

(3) that this research would advance ecosystem science in general and therefore be of interest to the ecological scientific community; and

(4) this research would improve the management of the ecosystems on DoD lands and waters, including conservation of biological resources, compliance with environmental laws and regulations, and restoration of disturbed areas.

A. SUPPORT FOR THE WORKING HYPOTHESIS

A major outcome of the workshop is that the participants supported the working hypothesis. Participants included 15 leading ecological and environmental scientists and three representatives of DoD land and resources managers. More than that, there was overall agreement that the requirement for ecosystem management on DoD lands and waters presented major opportunities, because:

- DoD lands and waters include many unusual and unique ecosystems, valuable to advance ecosystem research.

- In-place ecological research, involving both military and non-military personnel, demonstrates that military mission activities and ecological research can proceed together. This in-place research provides a foundation which can be expanded to include the findings of the workshop participants.

- The requirements for mission readiness provide ecosystem research opportunities, i.e., activities on DoD lands cause disturbances that provide the basis to gain insight into ecosystem processes. These insights, obtained by integrating scientific research with land management, lead to adaptive improvements in management, or the concept of adaptive management. Over time, iterations of this sequence become a cycle of:
  - mission activities create disturbances that are studied (through collaborative research and monitoring) to reveal ecological principles;

- these principles guide management adaptations for less disturbing mission activities (or disturbances more effectively mitigated/ameliorated); and
- these insights, obtained by integrating scientific research with land management, lead to improvements in that land management.

- The workshop avoided redundancy with previous studies and built on existing experience, including:
  - There is a strong background of DoD experience and personnel in natural resource management that provides an excellent basis to develop future work.
  - Ecological research and monitoring conducted by private sector organizations, in cooperation with DoD professionals, have demonstrated that military mission activities and science could proceed together. Examples include: the substantial academic studies at Fort Carson; the collaborative conservation science investigations at Eglin AFB leading to protection of biodiversity; and the ecosystem-based planning for the future of Camp Pendleton.

- DoD advanced technologies (such as GIS and remote sensing, environmental modeling) have the potential for significant improvement in ecosystem research and management.

- DoD has opportunities to conduct ecosystem level experiments following valid statistical designs, rarely possible elsewhere, because DoD lands are comparatively large and under a single jurisdiction. Recognizing this set of congruences, the ecological scientific community is ready to respond to requests for proposal and statements of needs regarding ecosystem management and military training, restoration, conservation, compliance, and clean-up. The present situation makes possible immediate initiation of demonstration projects to prove the concepts of the working hypothesis. Participants agreed that the goal of ecosystem management on DoD lands is timely, because:
  - As discussed above, adaptive management, a component of ecosystem management, is the key to ecosystem management; and
  - Major advances have occurred in ecosystem land research during the past three decades, but opportunities to apply these to ecosystem management have been few, as have opportunities to test their validity.

B. GENERAL FINDINGS

There were many findings at the workshop. The following is a list of the general themes to emerge that are most relevant to the DoD mission and mission readiness.

- **Ecosystem science:** At the center of advances in recent decades in ecosystem science is the recognition that ecosystems are non-steady state. Previously, most management plans were based on the assumption that ecosystems exist under natural conditions in a single steady-state.

- Under the old paradigm, management to achieve the desired steady-state condition was simple: prevent all disturbances and allow the system to achieve its natural condition.
- Under the new paradigm, the focus shifts to sustainability of systems within the boundary conditions that are intrinsic and natural.

- **Adaptive management:** Given the new understanding that ecosystems are non-steady-state, a key ecosystem management issue is how to develop and execute adaptive management.

- **Disturbance as a key:** Even without human activities, ecosystems are subject to, and in some cases induce internally, changes in state. Rather than something to be managed to prevent, natural kinds and rates of disturbance or change should become a key to ecosystem research and management.

- **The Historic Range of Variation (HRV)** can become a baseline for determining whether certain kinds of ecosystem management are successful. In some cases, the management goal can be to maintain an ecosystem within its HRV. Therefore, an important aspect of ecosystem research, vis-a-vis ecosystem management, is the characterization of ecosystem trajectories and HRVs.

- **Disturbance caused by military training** can be a tool to learn how to manage for ecosystem to recovery. One approach would be to integrate ecosystem research with military training. The results of the research would provide new insights to improve management, so that the process is iterative.
  - More specifically, one DoD need is to restore landscapes disturbed during training so that these can be re-used in training. A management goal is to shorten the time for this recovery through restoration. Many suggestions were made concerning specific research activities that are conjectured to shorten this time.

- **Ecosystem health:** Ecologists have long searched for indices of the status, "health," or sustainability of an ecosystem, without much success. There is a need to understand what measures might serve, either in general or for a small number of ecosystems types, as such an index.
  - There are two kinds of indicators of ecosystem status: indicators that measure ecosystem status and indicators that are signals of change. Indicators are needed for both, but especially as an early warning of impending, undesirable changes in ecosystem status.
  - There are indices that could make use of DoD advanced technologies, so that the "health" of an ecosystem might be measured by advanced technologies in remote sensing, coupled with advanced computer techniques such as geographic information systems. However, these indices need to be tested for reliability, efficiency, accuracy, and cost-effectiveness.
  - From a biogeochemical point of view, a healthy ecosystem is one that conserves essential elements, and one that eliminates toxins. Therefore, another possible

indicator of biogeochemical health of an ecosystem is its ability to purify air and water (e.g., nitrate removal from bulk precipitation).
- Forecasting models are fundamental to successful management. However, ecology has been primarily an observational endeavor composed of a diverse and idiosyncratic range of studies, often uncoupled to each other and to theory. There is certainly a great increase in the number and kinds of models, and in the focus of research and publications on ecosystem models. However, many of these models are new and there has not been adequate time or funding available for appropriate tests of models. A clear need remains in ecosystem research to improve the linkage between formal theory and observations. Additionally, many of these forecasting models do not exist, and the basic research needed to formulate them is often yet to be done. This may be particularly true for the added stress of military operations on the landscape.
- Disturbance regimes on DoD lands can provide testbeds for the development and validation of models to aid in forecasting and understanding.

- **Ecological Thresholds**: It has been generally assumed in environmental laws and policies that there is no ecological threshold. However, some studies now indicate that thresholds indeed exist. Where these occur, they can become powerful tools to create a priority for environmental work and to determine the likely quantitative effect of chemical concentrations. Thus, research gaps include determining when thresholds occur (for what phenomena and at what levels). More specifically,
  - It is important to determine what are the thresholds of frequency and amplitude of disturbances above which biogeochemical cycles cannot recover naturally or by intervention.

D. KEY FINDINGS: RESTORATION, TRAINING, AND ECOSYSTEMS
Scientific understanding of ecosystems has the potential to provide methods to speed up and improve restoration. However, to achieve this, several research areas must be addressed. These include:

- Manipulation of biogeochemical characteristics of a site can aid in habitat restoration. In particular, nutrient availability can be manipulated to aid in recovery of vegetation. A research gap is determining how to make use of this understanding to improve ecosystem restoration.

- Rehabilitation of frequently-disturbed areas will usually involve restoration to an early successional stage. It is important to determine the biogeochemical consequences of maintaining a habitat in an early successional stage.

- In some cases, introduction of plants and microorganisms can facilitate habitat restoration. These include native, introduced, and “engineered” organisms. To apply this, it is necessary to determine which species are most useful in specific contexts, without risk of undesirable side effects (such as introduced plants and organisms becoming so successful as to be pests). Note that, in a larger context, this finding concerns the interrelationships between biodiversity and biogeochemical cycles.

- Restoration sometimes requires manipulation of the physical condition of the land — restoring drainage channels, eliminating effects of erosion, etc. Military technologies, for example the use of munitions in training as well as dozens of other possible restoration methods, could be constructively used to restore or control natural biogeochemical and hydrological cycles. This requires tests and development.

E. KEY FINDINGS: BIOGEOCHEMICAL CYCLES, SPATIAL SCALES

- Nutrients can be manipulated to change competitive relationships among species, thus affecting the success of selective species. This manipulation includes decreasing as well as increasing nutrient availability, altering the ratio of nutrients and the storage location and form. Thus it is more than simply fertilization of land and waters. This manipulation in turn can affect restoration. In any specific situation, some species of vegetation will be more efficient in restoration than others. While this idea is appealing qualitatively, a research gap is to determine how to make use of chemical cycling to alter the balance of species in a way that favors rapid restoration. However, there is a danger in rapid generation, for example many of the most rapid response organisms will be exotics.

- What species are present affects the kind and rates of restoration of biogeochemical cycles. The reestablishment of desired biogeochemical cycles in a disturbed area therefore depends on the availability of colonizing species. A research gap is: how to promote the persistence and migration of such colonizing species and particularly influence the process so that native species can out compete exotics.

- In general, the historical range of variation of biogeochemical cycles is not yet adequately understood, nor are the effects of such variation of biological diversity understood.

F. KEY FINDINGS: BIOLOGICAL DIVERSITY

Biological diversity, including the conservation of specific endangered species, is an important concern on DoD lands and waters. Disturbance regimes, unique or rare ecosystems, and jurisdictional control to allow for valid experimental design offer the potential to improve the scientific understanding of the ecosystem role of biological diversity. The following illustrate some of the questions, gaps, and issues.

- One school of thought is that if you manage for ecosystem integrity; and resulting health, conservation of biogeochemistry, and biodiversity will be maintained. This is unproven, however, and must be treated as a hypothesis to be tested.
  - As an example, it might be that activities that promote conservation of chemical elements required for life might be inconsistent with activities to promote overall conservation of biological diversity. As another example, see the discussion of

discussion of the two schools of thought regarding disturbance and diversity, below.

- While there is increasing interest in conserving total biological diversity, it is not possible to measure total diversity directly. Therefore, some proxies or indices must be developed; this is a research gap.

- Operational indices of total species diversity may not be species; instead they might be habitats or environmental factors. It is important to develop and test the efficiency, reliability, and accuracy of a small set of easily measured physical variables that predict trends in biodiversity. For example, in riparian areas, the amount of edge habitat relative to total area of concern will likely be a good predictor of biological diversity.

- It is accepted as axiomatic within the ecosystem management community that: (1) biodiversity is an important feature in ecosystem sustainability; (2) biodiversity is being lost in many systems; and, (3) protecting and enhancing it is a worthy goal. There is, however, little scientific research that defends axiom (1).

- There are two schools of thought regarding disturbance and diversity. One argues that diversity is maximized and its persistence enhanced by minimizing disturbance. This is an extension and consequence of steady-state theory. Another, called the intermediate disturbance hypothesis, argues that maximum diversity occurs under moderate but not extreme levels of disturbance. These two hypotheses require testing for a variety of ecosystems. Note that if the intermediate disturbance hypothesis is correct, then a program to maximize the conservation of biodiversity could produce an ecosystem that was not conservative in terms of chemical elements.

- It is generally accepted that the loss of some species can be a major factor in future ecosystem function, but some evidence suggests that, at least in some cases, the loss of a dominate species has had little effect on biogeochemical cycling and the persistence of other species.

- The conservation of specific, individual endangered species and conservation of total species diversity are two different goals. If resources for conservation are scarce, then decisions have to be made on where to direct those resources. Expenditure on rare and endangered species may close off options for expenditures elsewhere.

- Recently developed methods increase the efficiency of land allocation to conserve biological diversity. These approaches could be used on DoD land to determine which lands, and how much land, is required to satisfy the needs for biological conservation, while at the same time meeting the requirements of the DoD mission. In theory, these approaches could lead to an understanding of the minimum area required to be set aside for biological conservation, allowing as much land for uses other than solely conservation of biological diversity. However, these methods require further tests.

- Especially on modern landscape subjected to strong human alterations, ecosystems tend to exist as patches or isolated "ecological" islands. A theoretical basis exists for the relationship between the area of an ecological island and species size, but research is required to determine the required patch size for specific groups of species, as well as the utility of corridors that connect patches or the maintenance of ecosystem function. Research of these topics is another way that the land required to meet biological conservation goals could be minimized and the effort made more efficient.

- Central to the conservation of endangered species is quantitative estimates of the probability of extinction. To date, most attempts to provide these estimates have considered only the characteristics of a population abstracted from its environment. A research gap is to develop methods to estimate the probability of extinction of specific endangered species within an ecosystem context.

II. Introduction: Management-Scale Ecosystem Research

> **Ecosystem Management**
> Ecosystem management (EM) is: a goal-driven approach to environmental management that is at a scale compatible with natural processes; is cognizant of nature's time frames; recognizes social and economic viability within functioning ecosystems; and is realized through effective partnerships among private, local, state, tribal and federal interests. Ecology is the supporting science for EM. EM considers the environment as a complex system functioning as a whole, not as a collection of parts, and it recognizes that people and their social and economic needs are part of the whole. EM therefore draws on a collaboratively developed vision of desired future ecosystem conditions that integrates ecological, economic, and social factors. The overall goal of EM is to maintain and improve the sustainability and native biological diversity of terrestrial and aquatic, including marine, ecosystems while supporting human needs, including the DoD mission.

The purpose of our pre-workshop paper "Considerations of the State of Ecosystem Science and the Art of Ecosystem Management" was to provide background for, and stimulate discussion at the Management Scale Ecological Research Workshop (MSERW) held June 3-5, 1997 at Airlie House in Warrenton, Virginia. The paper provided an overview of the current state of ecosystem research and ecosystem management both on the micro and macro level, indicated major issues, scientific questions, gaps in understanding and knowledge, and opportunities for the future. We considered the utility of ecological research as an integral part of ecosystem management and provided some examples of such. We encourage readers to review this document before proceeding with the post-workshop paper, "Management-Scale Ecosystem Research: Findings and Recommendations". Although the pre-workshop paper was intended to be read first by the participants in the workshop, its eventual audience will be those who will administer, support, or conduct ecosystem management and may not be trained in ecosystem science.

To provide a perspective on the information provided in both papers, we shall review the overall goals of the MSERW.

The Department of Defense (DoD) is required by the Deputy Under Secretary of Defense for Environmental Security to ensure that ecosystem management becomes the basis for future management of all DoD lands and waters (DUSD(ES) 8 August 1994 memorandum to all services). In addition to this mandate, the DoD has identified a number of user requirements that relate to the continued maintenance of training and testing facilities, as well as preservation and enhancement of natural resources under its control. All of these user requirements relate in some way to the concept of ecosystem management.

The goal of the MSERW was to help DoD attain these objectives by identifying gaps in ecological knowledge and corresponding research opportunities. The objectives of the workshop were to: (1) characterize the status of ecological research at the management scale; (2) identify ecological research needs and opportunities to better address DoD user needs; and (3) link academic and other researchers with the user communities of the DoD and the Department of Energy (DOE).

The charge to the workshop was to consider biophysical phenomena, and not to consider social dynamics (social, cultural, and economic) associated with ecosystem management.

For those who have not had an opportunity to read the pre-workshop paper, we will repeat its significant points in this introduction. Boiled down to the basics, ecosystem management means a focus on certain structural features, certain processes, and certain dynamic properties of ecosystems. The structural features include: biological diversity, soils (or substrate of aquatic systems), and biological structural features (such as the kind of forest stand structure or a kelp bed structure). Ecosystem processes include: chemical cycling and population dynamics that lead to replacement and maintenance of a species; ecological succession (development of an ecosystem over time); and responses of ecosystems to characteristic disturbances and sources of variation (fire, storms, etc.) including rare and uncharacteristic events. Each of these broad subject areas were represented by experts at the workshop. Key ecosystem management issues and concepts addressed at the workshop were: biodiversity; ecosystem sustainability; experimental design as a part of management; and DoD and ecosystem management.

A. BIODIVERSITY

This concept has attracted great public attention and is seen by some as a central factor of ecosystem management. In general usage, this term has several meanings, including:

(1) conservation of specific endangered species or subspecies as stated in the federal Endangered Species Acts and related acts;

(2) conservation of the present number of species (referred to as "species diversity conservation");

(3) conservation of the present or some otherwise desired number of habitats (referred to as "habitat conservation"); and

(4) conservation of the present or some otherwise desired degree of genetic diversity (referred to simply as “conservation of genetic diversity”).

Biodiversity, although often discussed in terms of the conservation of total diversity (especially in No. 2 above), in practice often becomes an attempt to preserve a single species (No. 1 above). Sometimes a biodiversity argument is used as a surrogate for some other issue.

Biodiversity has strong popular appeal and has a strong legal basis. Much work done under the rubric of ecosystem management flows from the belief that biodiversity is the single rationale for management. This is not necessarily true, and can lead to several traps, including that of focusing on a single species and not conducting management on an ecosystem scale.

B. BIOGEOCHEMICAL CYCLES

Traditional concerns of ecosystem ecologists — biological productivity and chemical element cycling — have matured into the field of biogeochemistry, and in this process biogeochemistry has become more tightly linked to related disciplines such as marine and terrestrial geochemistry, atmospheric chemistry, and microbiology. A driving force for this integration has been the realization that organisms are a dominant factor in chemical element cycling and storage — on both a local and a global scale — and therefore regulate many aspects of global processes.

C. ECOSYSTEM SUSTAINABILITY

Instead of a focus on biodiversity by itself, ecosystem sustainability represents a focus on a set of ecosystem characteristics, especially ecosystem resilience, persistence, and integrity. Focusing on ecosystem sustainability can lead to appropriate levels of concern and, in fact, to conservation of biodiversity.

D. EXPERIMENTAL DESIGN AS A PART OF MANAGEMENT

An assumption of ecosystem management is that each new policy results in an experiment. This leads to the question: What is the appropriate design of experimental ecosystem management? (Most likely, this will involve several management approaches undertaken at the same time, along with appropriate controls.) In addressing this issue, the participants will look at the concept of ecosystem management as adaptive management. Adaptive management involves:

(1) initial reconnaissance;
(2) baseline measurements;
(3) development of initial policies and practices based on (1), (2) and (3);
(4) research to determine the extent to which initial policies and practices are effective.
(5) monitoring of key factors;
(6) analysis of spatial and temporal variation and patterns of key factors; and
(7) modification of policies and practices based on (4), (5), and (6).
(7) The new policies and practices lead to a new for research, so that the process becomes iterative, and research is integrated within management.

E. DOD MISSION & ECOSYSTEM MANAGEMENT

A question to be answered by ecosystem management trials is: Is it possible to do manipulations required as part of the DoD mission while conducting ecosystem monitoring and research relevant to ecosystem management?

(1) Cleanup: What kind of ecological research could go on during a cleanup phase?
(2) Military training and natural ecosystem management: How can these be accomplished together? How can the latter help the former?
(3) Management consistent with societal expectations: Can we manage for aesthetics of the lands, consistent with the mission of DoD?

III. ECOSYSTEM MANAGEMENT

Earlier in this century, it was believed that natural ecosystems remained at a steady-state unless disturbed by what were taken to be external and negative events. The steady state was assumed to have a constant amount of organic matter, a fixed storage and flow rate of each chemical element required by life, and a fixed level of biological diversity. In addition, it was believed that once the steady-state condition was reached it had the maximum organic matter and maximum biological diversity. The concept assumes that an ecosystem is a completely deterministic system without risk, chance, or uncertainty. Under this concept, the goal of ecosystem management was to maintain a steady- state; change in the state of an ecosystem was undesirable and a management goal was to prevent change. This lead to such broad landscape scale policies as fire suppression on forested lands. One of the primary changes that has taken place in ecosystem science during the past three decades is an abandonment of the belief that ecological systems are characterized by a single fixed, steady-state, and are completely deterministic systems without risk and uncertainty. Today, ecosystems are assumed to be open, without a single steady-state, and subject to variation from both internal and external factors. Environmental variability is now understood to be a key feature of any ecosystem. Moreover, it is now understood that ecosystem variation can be a key factor in ecosystem management. In fact, variance (s^2) might be considered a key feature to be measured as an indicator of ecosystem health.

A. THE CONCEPT OF ECOSYSTEM MANAGEMENT

Ecosystem management (EM) considers the environment as a complex system functioning as a whole, not as a collection of parts. It is a goal-driven approach. The overall goal of EM is to maintain and improve the sustainability and native biological diversity of terrestrial and aquatic, including marine, ecosystems while supporting human needs.

Under the old steady-state paradigm, the effects of management were simple to measure: One need merely compare the effects of a human action on an ecosystem to the condition of an ecosystem at its single, fixed, steady-state. Under the new paradigm, one instead must ask questions about how a human action changes the temporal trajectory of the system (that is, how it will affect the rate and direction of ecosystem changes over time). This argues for the establishment of long-term monitoring of ecological systems, and for maintaining controls as well as treatments, so that the effects of management policy can be determined. For example, some combination of (1) side by side, (2) before and after, or (3) “above and below” along some environmental gradient. These are the primary design tools used in setting up ecosystem management experiments.

An important aspect of ecosystem research, vis-a-vis EM, is the characterization of ecosystem trajectories and historic ranges of variations. Ecosystem management takes cognizance of nature's time frames; therefore in EM, actions take place at a time and space scale compatible with natural processes. EM recognizes social and economic viability within functioning ecosystems and is realized through effective partnerships among private, local, state, tribal and federal interests.

As stated earlier, EM means a focus on certain structural features, certain processes, and certain dynamic properties of ecosystems. The structural features include: biological diversity, soils (or sediments of aquatic systems), and biological structural features (such as the kind of forest stand structure or a kelp bed structure). Ecosystem processes include: chemical cycling and population dynamics that lead to replacement and maintenance of a species. Dynamic properties include: ecological succession (development of biological communities of an ecosystem over time); response of ecosystems to characteristic disturbances and sources of variation (fire, storms, etc.) and to rare and uncharacteristic events. Cast in even simpler terms, ecosystem management in practice concerns the sustainability of biological diversity and biogeochemical cycles, including the restoration of diversity and chemical cycling following disturbances.

Science can proceed in two ways in relation to management issues: by identifying a list of fundamental scientific questions and seeking to find where these might fit with management goals (a bottom up approach); or by identifying the management goals, and determining what scientific research is necessary to make adaptive management possible (a top down approach). There was general agreement at the workshop that a top down approach should be used for DoD concerns, i.e., consider first the DoD problems, then identify the research gaps.

B. ECOSYSTEM MANAGEMENT AND ECOSYSTEM RESEARCH

Ecosystem management is adaptive management, meaning that intrinsic components are: initial reconnaissance, baseline scientific measurements, scientific based monitoring of key variables, and ecosystem research. These lead to adjustment in policy which in turn leads to new ecosystem experiments and which require new research. The combination of research and policy adjustment is an ongoing process. In the past, the general approach to management of natural resources has been based on plausibility: If a management action seemed reasonable, it was accepted as appropriate and done, without attempts to determine whether the action was successful. It is now recognized that each new management action can be treated as a scientific experiment. Therefore, ecosystem research must be integrated in the management process. With this research, the management process can be adaptive because management actions can be adjusted as the degree of success of an approach is learned. However, this being said, there has been little done to integrate adaptive ecosystem management with ecosystem research. Therefore, a key ecosystem management issue is how to develop and execute adaptive management, a management process that learns and makes mid-course corrections as time passes.

From this perspective, EM is an iterative procedure. It begins with prevailing scientific tenets about how ecosystems function. These are tested during the process of ecosystem management. This leads to an increase in knowledge which forms a revised set of scientific tenets. This understanding then guides the next stage in management, i.e., it leads to "mid-course" corrections in the management procedures. And so the process continues. At any one time, there is a basis in present scientific understanding for present management practices, but practices are improved as knowledge is gained. The process is analogous to the treatment of disease in medicine; it is a well-known procedure in many fields. It is new to ecosystem management only in the sense that it has rarely been applied in a formal manner.

1. Components of Ecosystem Research:

In most cases, ecosystem research consists of the study of:

- **Production of organic matter** and the factors that control it at the ecosystem level. Production of organic matter includes both primary production, which is the production of the autotrophs, (those that make their own organic compounds from inorganic compounds and a source of energy), and secondary production, the production of heterotrophs (those that must feed on other organisms).

- **Decomposition of organic matter** and associated chemical cycles and the control that chemical cycles exert over productivity and diversity; and, conversely, the effect of productivity and biological diversity on chemical cycling (What chemical elements limit and/or control production and diversity, and under what conditions?; When does total biomass and/or biological diversity affect chemical cycling, including storage and loss of specific chemical elements?).

- **Key characteristics of communities**, which include: (1) the number of species, and therefore species diversity; (2) the connection among these species, which is usually stated in terms of trophic levels or food webs; and (3) biological diversity and the factors that alter and determine diversity and dominance, especially the extent to which there are feedbacks such that chemical cycling affects the biotic community which in turn affects chemical cycling.

- **Patterns of change** in ecosystems over time, primarily the study of ecological succession (the process of development of an ecosystem).

- **Spatial structure of the habitat** (the physical structural elements of the environment) and the biota, how these change over time, and their influence on biological production and diversity (What is the effect of structural and temporal environmental heterogeneity on biological diversity?).

- **Systems attributes**, including: (1) the scaling issue: What is the minimum system that can sustain life over long periods? Is an attribute of that system a hierarchy of interconnected subsystems with different spatial scales? and (2) the stability-sustainability issue: To what extent are these systems steady-state or non-steady-state? In what ways are these systems stable or quasi-stable; deterministic or stochastic? To what extent are these systems controllable?

C. THE DOD MISSION & ECOSYSTEM MANAGEMENT

DoD has opportunities to conduct ecosystem level experiments following reliable statistical designs, rarely possible elsewhere, because the DoD lands are comparatively large and under a single jurisdiction and based on an acceptance of a certain level of disturbance. Questions to be answered regarding the DoD mission and ecosystem management are:

- Is it possible to do manipulations required as part of the DoD mission, that are often not possible on other lands, while also conducting ecosystem monitoring and research relevant to ecosystem management?

- What kind of ecological research related to environmental toxicity could go on during a clean-up phase?

- How can military training and natural ecosystem management be accomplished together? How can the latter help the former?

- How can management practices assure for maintenance of aesthetics of the lands, where the DoD lands are part of the public scenery, and be consistent with the mission of DoD?

IV. ECOSYSTEM RESEARCH GAPS AND OPPORTUNITIES

A primary goal of the workshop was to identify major ecosystem gaps and opportunities essential for ecosystem management. Another goal was to better understand these systems, so that they can be better managed, with an emphasis on those that were directly relevant to the DoD mission and could benefit from special characteristics of DoD land and jurisdiction.

Research gaps and opportunities were approached through four major themes: biogeochemical cycles, biological diversity, spatial scales, and theory and monitoring. The workshop participants worked in groups associated with each of these categories, and were asked to identify gaps and opportunities for each category. Most of the research gaps and opportunities are grouped by these categories. However, some general themes arose — gaps and opportunities identified by most or all of the groups. These general themes are presented first.

A. GENERAL CONCEPTS AND RESEARCH GAPS

1. Ecosystem Health

Ecologists have long searched for indices of the status, "health," or sustainability of an ecosystem, limited success. There is a need to understand what measures might serve, either in general or for a small number of ecosystems types, as such an index. A question arises from this consideration: Can a single index be developed that would indicate overall ecosystem health?

There are two kinds of indicators of ecosystem status: indicators that measure ecosystem status and indicators that are signals of change (the canary in the coal mine). Indicators are needed for both, but especially as an early warning of impending, undesirable changes in ecosystem status.

Possibly, the indices that could make use of advanced technologies, so that the "health" of an ecosystem might be measured by remote sensing, using advanced computer techniques such as geographic information systems and environmental modeling technologies. For example, it is possible to monitor changes in vegetative cover and vigor (e.g., water and temperature stress) by remote sensing. The research gap is the degree to which such measures are adequate indices of ecosystem health. By extension, this leads to the question: Can DoD advanced technologies be applied to provide better (faster, more accurate, and more easily used over large areas) indices of ecosystem status?

2. Disturbance as a Key

Even without human activities, ecosystems are subject to, and in some cases induce internally, changes in state. Rather than something to be managed to prevent, these natural kinds and rates of disturbance or change can become a key to ecosystem research and management. For example, the historic range of variation (HRV) can become a baseline for determining whether certain kinds of ecosystem management are successful. In some cases, the management goal can be to maintain an ecosystem within its historic range of variation.

How an ecosystem responds to a specific change can provide keys to the sustainability of the ecosystem and therefore to its management. Disturbances that occur during DoD use of lands and waters can be integrated into ecosystem research as part of a suite of experiments. Activities that alter the state of an ecosystem could be applied in a way that would make them part of a valid experimental design.

This leads to a need to understand: What is the natural disturbance history of a site and how does this differ from the anthropogenic disturbances? Are the effects of natural and anthropogenic disturbances interactive?

3. Ecological Thresholds

A threshold is a level of some chemical compound below which there is no measurable affect over an appropriate time span on an ecosystem or on one of its components. It has been generally assumed in environmental laws and policies that there is no ecological threshold. For example, the clean water act requires zero discharge and therefore assumes no threshold. Although there are many laboratory studies for individual organisms and populations of single species concerning their response to specific environmental factors, there are few studies at the ecosystem level to determine whether thresholds exist. Thus there is a general research gap: When do thresholds occur? What is the threshold level of some compound? How do you define thresholds of ecosystem processes?

4. Opportunities Unique to DoD

DoD could be a test bed for best-ecological land management practices by:

- becoming an integral part of the nationwide network of monitoring sites, where this does not conflict with the DoD mission; and

- exploring the use of DoD's own cutting edge technology, e.g. remote sensing and environmental modeling technologies, to address DoD ecosystem management problems.

B. BIOGEOCHEMISTRY

Chemical cycles exert control over productivity of organic matter and biodiversity; conversely, productivity and biological diversity exert control on chemical cycling. Much of biogeochemistry research focuses on the physical and chemical factors that limit the distribution and abundance of organisms. At a basic level this question translates to: What factors limit primary productivity, community respiration, and nutrient availability? Primary production is a key feature of ecosystems because it supplies all the chemical energy that is required for life processes. These reactions are carried out by algae, plants and bacteria, and include both photosynthesis and chemosynthesis in which inorganic carbon dioxide is converted to organic carbon that can be used by all forms of life. Organisms are a dominant factor in chemical element cycling and storage on both a local and a global scale, and therefore regulate many aspects of global processes.

Because organisms and chemical cycling are intimately coupled in ecosystems, neither can be understood in isolation from the other. These interrelationships raise several scientific issues:

- What chemical elements limit and/or control production, decomposition, and diversity, and under what conditions?;

- When does total biomass and/or biological diversity affect chemical cycling, including storage and loss of specific chemical elements?; and

- Are the simultaneous sustainability of biological diversity (as it is currently practiced) and biogeochemical cycles possible? Or will the attempt to achieve one lead to a failure to achieve the other?

From a biogeochemical point of view, a healthy ecosystem is one that conserves essential elements, and one that eliminates toxins. Therefore, another possible indicator of biogeochemical health of an ecosystem is its ability to purify air and water (e.g., nitrate removal from bulk precipitation).

1. Knowledge Gaps Related to Habitat Restoration

A key question regarding chemical cycles and habitat restoration is how do you best utilize or manipulate biogeochemical characteristics of a site to aid habitat restoration. Related questions and knowledge gaps include:

- Rehabilitation of frequently-disturbed areas will usually involve restoration to an early successional stage. What are the biogeochemical consequences of maintaining a habitat in an early successional stage? Will this largely be a matter of changes in turnover rates with differential effects on different elements?

- Can nutrient availability be manipulated to aid the recovery of vegetation or slow the invasion of exotic species that is a logical consequence of human disturbance?

- Is there a role in habitat restoration for introducing plants or microorganisms (native or exotic) that have unique biogeochemical properties?

- What are the thresholds of disturbance above which biogeochemical cycles cannot recover naturally or by intervention?

- Can military technologies, even the use of munitions in training, be constructively used to restore or control natural biogeochemical and hydrological cycles?

2. Space and Time in Restoration

The reestablishment of desired biogeochemical cycles in a disturbed area will depend on the availability of colonizing organisms. A research gap is: how to promote the persistence and migration of such colonizing species. In part the answer lies in maintaining habitats that serve as refuges for colonizing organisms. They may be areas that require a natural disturbance regime (such as prescribed burns) and protection from disturbances resulting from training exercises or other human activities.

- Is there an optimal patch size and distribution for given organisms or communities?

- How do physical and chemical disturbances affect the biogeochemical processes of a site, such as the loss of nutrients to air, ground water, and runoff from soil?

- How does habitat fragmentation and connectivity influence biogeochemical function?

3. Chemical Cycling and Biodiversity

- What are the biogeochemical feedbacks of vegetation management strategies, such as the effects of fire or timbering practices on soil water balance and nutrient loss and/or cycling?

- Is there a biogeochemical basis for a keystone species? For example, if you manage for a single 'keystone' species, or a suite of species, will the rest of the ecosystem take care of itself? Alternatively, how many trophic links are necessary between keystone and other species before regulation of keystone species also regulates general nutrient cycling?

4. HRV (Historic Range of Variation) of Biogeochemical Cycles as an Index of Sustainability

In general, the historic range of variability of natural biogeochemical processes is not yet adequately understood. However, specific ecosystem research projects conducted during the past decades demonstrate that it is feasible to determine this range. There is a need to understand this range for a variety of ecosystems, and to attempt to develop generalizations concerning ecosystem type, environmental conditions, and the historic range of variation. A number of ecosystem research gaps arise from these considerations, including:

- What are the consequences of exceeding the historic baseline of nutrient, sediment and organic matter loading or depletion (unloading)?

- What are the thresholds of contaminant loading that impede biogeochemical cycles and above which the biological community cannot detoxify?

- How do disturbances to surface and subsurface hydrology above historic levels and thresholds impair biogeochemical processes such as carbon cycling and nutrient transport?

5. Measurement Issues

What cost-effective measurements of biogeochemical processes are useful to gauge the success of restoration projects? (On the land, basic information on the mapping of soil types is necessary for restoration. This is an important information gap, but not a research question.)

A research gap is the determination of what are the biogeochemical indicators of ecosystem "health?" For example, could the total rate of carbon fixation x species diversity be such a measure, i.e., $H = n*NPP$ where n is the number of species and NPP is the total net carbon fixation (also known as net primary production). A suite of tools could be developed that range between simple indicators of a change in condition that provide little information about causality (analogous to monitoring body temperature) to more costly tools used only when a more definitive diagnosis is required. A research-development question is: What diagnostic tools would be useful in developing indices of the structural and functional integrity of biogeochemical cycles?

Among the suggestions were the possibility that nitrate flux from an ecosystem may be a useful measure of ecosystem health. Typically, organisms within an ecosystem will use as much nitrogen as is available. Thus, a large output of nitrogen suggests an equivalent of a pathology in terms of biological production or storage. Another suggestion is that monitoring the changes in ratios of essential elements, such as the nitrogen phosphorus ratio, can be a useful indication of the balance or imbalance of nutrients. A third suggestion: Signature lipid analysis, especially polyunsaturates, of soil and water samples can provide information about the physiological state of the microbial community and the bioavailability of the essential nutrients.

C. BIOLOGICAL DIVERSITY

Biological diversity has attracted great public attention and is seen by some as a central factor of ecosystem management. Biodiversity has strong popular appeal and has a strong legal basis. A lot of work done under the rubric of ecosystem management flows from the belief that biodiversity is the single motivation and rationale for management. This is not necessarily true, and can lead to several traps, including that of focusing only on a single species and not performing management on an ecosystem scale.

1. Biodiversity Measures: A Central Dilemma

The attempt to conserve total species diversity presents several scientific dilemmas. First, in general, it is not possible to measure total species diversity (to determine the complete list of species present in an ecosystem). Therefore, some proxies or indices of total species number must be developed. The development of such proxies that can be applied generally remains an unsolved research gap.

Operational indices of total species diversity may not be species; instead they might be habitats, or environmental domains. This raises the question: Is there a small set of easily measured physical variables that can be used to predict trends in biodiversity? The determination of such variables is a research gap. To measure biological diversity, and to develop baseline and monitoring programs, it is necessary to map these proxies in a spatially consistent manner. This has rarely been done; therefore a research gap is to determine the most efficient and accurate method to measure proxies for biological diversity.

Another research gap is the need to understand how to maintain a present level of biodiversity under different stressors, or to understand how specific stressors will affect the amount of diversity. For example, in some cases, moderate levels of disturbance appear to increase biodiversity, while no disturbance or high levels of disturbances tend to decrease biodiversity. The extent to which disturbance increases and decreases diversity is a research gap; while there are a few ecosystems for which some information exists about this topic, it is not possible to generalize at this time.

2. The Importance of Biodiversity to Ecosystem Sustainability

It is accepted as axiomatic within the ecosystem management community that: (1) biodiversity is an important feature in ecosystem sustainability; (2) biodiversity is being lost in many systems; and, (3) protecting and enhancing it is a worthy goal. There is, however, little scientific research that defends axiom (1), and therefore there is a significant lack of scientific agreement on some very basic questions, such as:

- How does biodiversity contribute to long-term stability and sustainability?

- When is losing a species (or a suite of species) a major factor in future ecosystem function, and when (if ever) is it essentially a non-event? How do ecosystems flex around a major species change, such as the loss of chestnut, passenger pigeon, or large grazers?

- How much genetic diversity is needed in order to achieve some assurance of stability, both in terms of species success and ecosystem sustainability? Is, for example, the fact that western white pine is being propagated now from a few blister-rust resistant strains a signal that the species may be saved from a fate similar to the chestnut, or does it indicate that our efforts to save the species are so narrowing the genetic base that the species is being further imperiled?

The conservation of specific, individual endangered species and conservation of total species diversity are two different goals. It is generally assumed that they coincide, but they need not. If resources for conservation are scarce, then decisions have to be made on where to direct those resources. Expenditure on rare and endangered species may close off options for expenditure elsewhere, e.g., resulting in declines in populations of species not yet rare or threatened. These issues become of particular concern where rare species might signal other environmental problems.

3. Determining Biodiversity Priority Areas on DoD Lands

DoD lands and waters contain endangered species as well as unusual, rare, or unique ecosystems. They present challenges and opportunities regarding biodiversity. In the past, protected areas have been established to conserve wilderness, spectacular scenery, rare and endangered species, or simply because they were available and had little potential for extractive uses such as farming, forestry or mining. This has led to a biased representation of biodiversity in the network of protected areas. Species and ecosystems occupying rugged and remote areas are much better represented than species and ecosystems occupying land suitable for agriculture, forestry, etc.

A more systematic approach uses the idea of complementarity to identify a sub-set of areas within a region that together maximize the biological diversity of that set. Maximum diversity, or richness, is the objective of the set of areas, but any one area is assessed for inclusion in the set according to the new features (species, habitats, ecosystems, etc.). The complementarity of an area is the number of new features it contributes. Thus, for example, an area poor in species may have a high complementarity value if those species are not already represented, or sampled, in the current set of areas.

These newly developed approaches seek to improve the allocation of land. These approaches could be used on DoD land to determine which lands and how much land are required to satisfy the needs for biological conservation while at the same time meeting the requirements of the DoD mission and allowing as much land for uses other than solely conservation of biological diversity. Research is needed to test the efficiency of these methods.

4. Effects of Spatial Scale and Landscape Shape and Form

There is much discussion about the size of areas required to conserve biological diversity and the shape and form of natural areas that will best conserve biological diversity, for example, maintaining corridors for migrations between habitats. Interest in these topics has grown rapidly and the amount of research has expanded in recent years, but much still needs to be learned.

The basic ideas extend back to the development of the theory of island biogeography, which tells us that, other things being equal, the greater the size of an island, the more species can be sustained there. On a modern landscape, areas suited to specific species tend to occur as isolated patches surrounded by land in other uses. These patches are called "ecological islands." It is generally assumed that establishing corridors among ecological islands effectively increases the area available to species and the variety of habitats available to them and should increase biological diversity.

A research question is: What are the more efficient shapes of ecological islands and connecting corridors for the conservation of biological diversity? Does maintaining such corridors increase biodiversity? How much area is enough to conserve either a specific species or to maintain overall biological diversity?

5. Conservation of Endangered Species

Since the greater the number of individuals, the greater the areas required to support them, a related question is: What is the minimum viable population for a specific species? In the past, many attempts to conserve endangered species have proceeded along two quite separate lines. One focuses on the natural history of a species and therefore considers carefully what is known empirically about the habitat requirements of the species. The other is a more formal approach, attempting to forecast effects of harvests and population size on the future condition of the species. The latter has primarily considered only factors related to that species's population characteristics abstracted from the environment. As an example, formal methods in the management and conservation of salmon to forecast future population size and set harvest levels have been based on mathematical models that ignored interactions with other species and all aspects of the environment except harvesting. Although scientific understanding has increased about the ecosystem context of an endangered species, management practices have changed little around the world during the last 20 years, and rarely has the ecosystem context been invoked in formal forecasting methods. Thus, a research gap is the need for improvement of theory that considers the ecosystem context for endangered species.

6. Minimum Viable Populations

One of the advances in conservation biology has been a consideration of what might be the minimum viable population of an endangered species. However, the emphasis of this work has tended to be on genetic factors, such as the likely consequences on future genetic variability of a population reduced temporarily to a very small number. But determination of a minimum viable population must also consider the ecosystem context, including interactions with other species, availability of essential chemical elements, and size and shape of the ecological island where the endangered species occurs. Examples of specific ecosystem-level research gaps concerning minimum viable populations are:

- What is the effect of competition between non-endangered species and exotic species on a specific endangered species?
- How does modification of a specific chemical cycle affect what can be a minimum viable population?

An important related topic is the effect of alien species (species that are introduced by human action and are not native to an area) on minimum viable populations, endangered species, and overall biological diversity.

7. Estimation of the Probability of Extinction

Central to the conservation of endangered species is quantitative estimates of the probability of extinction. Few attempts have been made to provide these estimates; most consider only the characteristics of a population abstracted from its environment. A research gap is to develop methods to estimate the probability of extinction of specific endangered species, given an ecosystem context. With this information, management of endangered species in a location could be prioritized and made more efficient. Other biodiversity research gaps include:

- What is the relationship between species composition and landscape processes such as: soil nutrient/chemistry; soil surface condition; water flow (ground and surface); microclimate (how do rates of change in landscape patterns relate to biodiversity)?
- What are the appropriate monitoring variables and strategies for biological diversity?
- Is there a small set of easily measured physical variables that could predict trends in biodiversity?

8. Management for Biodiversity

What is the role of biodiversity in sustaining ecosystem functions and processes, including biogeochemical cycles, biological productivity, physical structure of the habitat, and the processes of toxins and wastes? Some groups of organisms are indicators of the state of an ecosystem. For example, the species of ants present provide information about the soil structure; the species of plants present provide information about physical structure; vertebrates and invertebrate animals are indicators of the trophic structure; microbes are indicators of biogeochemical conditions. It might be possible to develop indices of ecosystem sustainability from knowledge of these relationships. Additionally, research is needed to asses the impact of military activities on biodiversity. These activities would include training and readiness activities.

D. SPATIAL SCALES AND STRUCTURAL PATTERNS

As stated earlier, one of the basic, general research gaps concerns the scaling issue — determining the minimum system that can sustain life over long periods. Is an attribute of that system a hierarchy of interconnected subsystems with different spatial scales? More specific research gaps related to spatial scales include:

- How does the scale and pattern (spatial and temporal) of disturbance events affect management decisions on an ecosystem basis?

- Can some DoD activities serve as "natural" disturbance surrogates for research on ecological disturbance regimes and patterns?

The issue of spatial and structural patterns connects to the other topics outlined here. For example, research gaps include:

- How does the maintenance of biodiversity depend on spatial scale, shape and form?

- What is the connection between spatial scale and the attenuation of ripple effects of disturbance events, for example, as related to home range of critical or keystone species?

- What is the relationship between spatial scale and pattern and the resilience and resistance of ecological systems, e.g. resistance and resilience formulated in the terms of good colonizers versus “bad” colonizers given above?

1. Biological Preserves

There has been much discussion in the past decade suggesting that the shape and size of a nature preserve must have important consequences. That there must be a minimum viable population implies that there must also be a minimum area for that population to inhabit. A few experiments have examined this question. Perhaps the best known is the study of the effects of the size of forest patches left after logging in the Amazon rain forest or the spotted owl issue in the Pacific Northwest. This work has focused mainly on birds. For these the results suggest that there are minimum sizes below which a species is no longer viable locally. Thus, an important research gap is to determine how ecosystem processes are affected by size and shape. Related questions include:

- Are there accepted ways to measure and rate landscape diversity patterns to provide useful management guides so that managers can aim for patterns that tend to reinforce ecosystem functions, processes, and sustainability?

- Typical scales of influence are: physiographic, watershed, catchment, and hill slope; the appropriate scaling indicators vary between them.

- How do ecosystem processes interact at different scales? Are there some ecosystem types for which hierarchical relationships are adequately developed and known? Some for which they are not?

- How do you define the extent of ecosystem boundaries? What are the spatial/temporal considerations of boundaries: ecological, political, socio/economic? How are their differences reconciled?

- Is there an optimum scale in time and space for management?

- Are there indicators we can monitor/measure that give an overall view of the health/warning status of ecosystems?

- Can we scale up information about ecological processes?

- What analytical, mapping and sampling approaches are appropriate at different scales? Is this most commonly a function of the management questions to be addressed? Or the type of ecosystem involved?

- How do you measure ecosystem processes at different spatial scales?

- How do you relate/integrate/normalize data (e.g., data maybe at different scales or represent different types of phenomena)?

- What are appropriate levels of accuracy, precision, and resolution for working with different scales?

- How do you achieve reproducible, defensible, comparable methodologies and data sets appropriate to scale?

- What effect do scale and pattern have on the most effective methods of measuring and communicating risk and/or ecosystem values?

- How does the temporal scale affect the value of ecosystem processes? (current generation versus future generation)

- How does the pattern and scale of the information about the ecosystem affect the perceived risk?

2. Opportunities for DoD Emphasis

Some DoD installations have the size and management ability to test the re-introduction of fire (for example), at something approximating historical ranges of interval and intensity (perhaps even size). Coupling research to these management regimes could help answer questions about the ecological effects of alternate fire regimes that would be exceptionally useful to all managers of similar ecosystems. DoD rehabilitation activities could then serve as surrogates or examples to help facilitate similar practice in other sectors.

DoD could explore the utility of long records (such as 70-year air photo records of military posts, LCTA, or other monitoring) for testing concepts such as the significance of keystone species or the reliability of early warning indicators on future ecosystem conditions. DoD could also use rigorous ecological methods for measuring the impacts of various military activities on: 1) urban centers of various sizes; 2) vehicle impacts on tank/training ranges; 3) pedestrian/hiking/camping traffic; or 4) forest clearance. This is useful for: 1) defending military land-management policies; and 2) designing for mitigation of military and civilian activities.

D. THEORY AND MODELING

Ecology has been primarily an observational endeavor composed of a diverse and idiosyncratic range of studies, often uncoupled to each other and to theory. Ecologists are confronted with a great number of species (approximately 1.4 million named), a great diversity of life histories of individual species, and many kinds of physical environments. Traditionally, ecologists working in one ecosystem have tended to focus on one set of questions while those working in another ecosystem have focused on another set of questions. In the history of ecology, ecological theory has done poorly in general in terms of accurate and realistic forecasts or as an aid to understanding ecological processes. Many ecosystem ecologists believe that the situation is improving rapidly. There is certainly a great increase in the number and kinds of models, and in the focus of research and publications on ecosystem models. However, many of these models are new and there has not been adequate time and funding available for appropriate tests of models. A clear need remains in ecosystem research to improve the linkage between formal theory and observations. The general research gaps related to models are summarized in Table 1.

Disturbances typically stress ecological inputs through a few stressed components. The characteristic stressed factors are: soil; above ground biological structure (such as the structure of a forest, shrubland, grassland); hydrologic features (such as stream channel shape, surface and subsurface runoff); toxic compounds concentration; concentrations of biological essential chemical elements; food webs; the atmosphere. Ecological "endpoints" — the dependent variables of interest, typically affected by the stressed factors — are biological variables which exist at all spatial and temporal scales, from the characteristics of population dynamics of species to characteristics of the ecological community, the ecosystem, and a landscape of a number of interacting ecosystems.

Disturbances have ecological impacts through mechanisms that include specific stressed factors. In order to understand the ecological impacts, it is necessary but not sufficient to understand the ways that the disturbances are transmitted through the stressed factors to the ecological endpoints. The reason for this is that ecological impacts are often the result of interactions among the ecological endpoints, and one must understand them as well.

Therefore, research gaps related to theory and models include:

- development of conceptual models that accurately and realistically describe the transmission of disturbances through the stressed elements to the ecological endpoints;

- integration of models with radically different time and space scales (distinguish between current, past and projected military uses of the land and those impacts due to other factors, such as acid rain or short-term changes in average weather conditions; there are models for each of these, but each utilizes its own time and space scales);

- research on disturbances in time and space as they relate to natural cycles; and

- integration of the understanding of natural frequency or temporal distribution of disturbances with projected military land use (if natural frequencies of disturbances can be predicted, one can time man-made disturbance so as to have as little adverse impact as possible. For example, if you know that projected use involves excavation and it is known that rain occurs heavily January through March, one knows then that excavation after this period is less likely to have adverse effects than excavations at the start of the rainy season.).

V. SUMMARY

This document presents the results of a workshop sponsored by the Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP), called The Management-Scale Ecosystem Research Workshop held June 2 through 5, 1997, at Airlie House, Virginia. It builds upon a background paper prepared for the workshop, *Considerations of the State of Ecosystem Science And the Art of Ecosystem Management* by Daniel B. Botkin, Patrick Megonigal and R. Neil Sampson. The workshop participants agreed that it was possible to do ecosystem scale research on military lands while operations are ongoing; that this research could be supportive of specific military missions and to overall military mission readiness; that this research could advance ecosystem science and therefore be of interest to the ecological scientific community; and that this research would improve the management of ecosystems on DoD lands and waters. Working in "breakout" groups, the participants developed lists of recommendations which are presented in this paper. The participants included some DoD land managers and there was agreement that existing projects on DoD bases could provide the basis for implementation of the concepts suggested here. This is an important and large task, for which the participants at the workshop provided some initial assistance, recognizing the need for follow-up activities that would lead to an integrated program of research and management.

Table 1: Research Needs Related to Theory

A. Tools that should be developed

Research Topic	D	M
Conceptual models (basic processes, ecosystem types, nearest neighbors).	x	x
Collect data for (i) model development, parameterization, and calibration, and (ii) model validation.	x	x
Integrate GIS with modeling.	x	
Link remote sensing with modeling.	x	
Generalize the concept of carrying capacity based on time-varying stochastic models.	x	x
Quantify cumulative impacts.	x	x
Integrate models with radically different time and space scales.	x	x
Develop interfaces between different models so they can be used in a coordinated fashion.	x	
Time disturbances in view of natural cycles.		x
Develop indices, surrogates, and endpoint measures.	x	x

D Particularly consistent with the theme of disturbance theory
M Particularly consistent with the theme of risk-based management

Table 2: Applications of Currently Available Theory

The following have to do with development of ecosystem management. The tools exist, but they have not yet been applied to ecosystem management. In this sense, the following is a list of development needs rather than research needs.

Research Topic	D	M
Error and uncertainty analysis	x	x
Statistical methods with minimal controls and replications	x	
Integrate GIS with modeling	x	
Link remote sensing with modeling.	x	

D Particularly consistent with the theme of disturbance theory
M Particularly consistent with the theme of risk-based management

There are recently developed statistical methods that minimize the necessary size of control groups and the number of replications. These need to be considered for use wherever possible because they may permit less data collection, or greater certainty in results, may cost less, and also may allow the use of existing data sets not previously believed useful, such as historic records, without the standard statistical experimental design.

V. GLOSSARY OF TECHNICAL TERMS

Adaptive management: Adaptive management is a procedure for the continuous incorporation of new, relevant information as it is collected and analyzed so that a new management plan is implemented as new scientific knowledge becomes available concerning the degree of success and failure of present activities. It is an iterative process that involves gathering knowledge and making mid-course corrections that lead to improvements in management over time.

Biological diversity: In general usage, this term has several meanings, including: (1) conservation of specific endangered species or subspecies as stated in the federal Endangered Species Acts and related act; (2) conservation of the present number of species (referred to as "species diversity conservation"); (3) conservation of the present or some otherwise desired number of habitats (referred to as "habitat conservation"); and (4) conservation of the present or some otherwise desired degree of genetic diversity (referred to simply as "conservation of genetic diversity"). Biodiversity, although often discussed in terms of the conservation of total diversity especially in #2 above), in practice often becomes an attempt to preserve a single species (#1 above).

Ecosystem management: a management approach that considers the environment as a complex system functioning as a whole, not as a collection of parts (e.g. populations, chemical elements). The overall goal of ecosystem management is to maintain and improve the sustainability and native biological diversity of terrestrial and aquatic, including marine, ecosystems while supporting human needs.

Ecosystem concept: The general definition of an ecosystem is: an ecological community and its local, non-biological environment. The ecological community is the set of species found within an ecosystem. These species interact through competition, through symbiosis (helping one another), and through a trophic food web — the food structure — who feeds on whom. These interactions can take place directly, through physical contact, or indirectly, for example, when individuals of one species affect the concentration of a chemical element required for life. The underlying idea of the ecosystem is that, for life to persist, there must be a flow of energy and a cycling of the chemical elements required by living things. These processes are not the attribute of any single individual, but of a community of individuals of many species and their local, non-biological environment. In the past, the management of natural, biological resources was often done from a focus solely on the species of interest, abstracted from the flow of energy and cycling of chemical elements, and any other aspects of the complexity of ecosystems.

Ecological threshold: the level of some chemical compound or population density below which there is no affect on an ecosystem or on one of its components.

Keystone species: generally speaking, a species that has a large effect on its community or ecosystem so that its removal or addition leads to major changes in the abundances of many or all other species.

Primary production: the production carried out by autotrophs, which make their own organic matter from a source of energy, usually sunlight, and inorganic compounds.

Secondary production: production by heterotrophs — all animals, including human beings, fungi, many kinds of bacteria, and many other small forms of life — who cannot make their own organic compounds from inorganic ones and must feed on other living things.

HRV (Historic Range of Variation): the boundary conditions for a parameter over the available historical record.