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Essays

Command and Control and the Pathology of Natural Resource Management

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Abstract: *As the human population grows and natural resources decline, there is pressure to apply increasing levels of top-down, command-and-control management to natural resources. This is manifested in attempts to control ecosystems and in socioeconomic institutions that respond to erratic or surprising ecosystem behavior with more control. Command and control, however, usually results in unforeseen consequences for both natural ecosystems and human welfare in the form of collapsing resources, social and economic strife, and losses of biological diversity. We describe the "pathology of natural resource management," defined as* a loss of system resilience when the range of natural variation in the system is reduced *encapsulates the unsustainable environmental, social, and economic outcomes of command-and-control resource management. If natural levels of variation in system behavior are reduced through command-and-control, then the system becomes less resilient to external perturbations, resulting in crises and surprises. We provide several examples of this pathology in management. An ultimate pathology emerges when resource management agencies, through initial success with command and control, lose sight of their original purposes, eliminate research and monitoring, and focus on efficiency of control. They then become isolated from the managed systems and inflexible in structure. Simultaneously, through overcapitalization, society becomes dependent upon command and control, demands it in greater intensity, and ignores the underlying ecological change or collapse that is developing. Solutions to this pathology cannot come from further command and control (regulations) but must come from innovative approaches involving incentives leading to more resilient ecosystems, more flexible agencies, more self-reliant industries, and a more knowledgeable citizenry. We discuss several aspects of ecosystem pattern and dynamics at large scales that provide insight into ecosystem resilience, and we propose a "Golden Rule" of natural resource management that we believe is necessary for sustainability: management should strive to retain critical types and ranges of natural variation in resource systems in order to maintain their resiliency.*

Comando-y-control y la patología del manejo de los recursos naturales

Resumen: *A medida que la población humana crece y los recursos naturales declinan, existen presiones para aplicar niveles crecientes de manejo de recursos naturales verticalistas y de comando-y-control. Esto se manifesta en los intentos de controlar los ecosistemas y en instituciones socioeconómicas que responden a los comportamientos erráticos o sorpresivos de los ecosistemas con más control. Sin embargo, el comando-y-control tiene usualmente resultados imprevistos tanto para los ecosistemas naturales como para el bienestar humano, tales resultados toman la forma de recursos que colapsan, conflictos sociales y económicos y pérdidas de la diversidad biológica. En el presente trabajo, describimos la "patología del manejo de los recursos naturales" (definida como una pérdida de la elasticidad del sistema cuando la magnitud de la variación natural en el sistema es reducida), que condensa los resultados ambientales-sociales-económicos insostenibles producidos por el manejo de recursos con una óptica de comando-y-control. Si los niveles de variación natural en el comportamiento de un sistema son reducidos a través de comando-y-control, entonces el sistema se hace menos elastico a las perturbaciones externas, lo cual resulta en crisis y sorpresas. Nosotros proveemos de varios ejemplos de esta patología en el manejo. Una patología extrema surge cuando las agencias de manejo de recursos, pierden de vista sus propósitos originales debido al éxito del uso de comando-y-control, eliminando la investigación y el monitoreo y concentrándose en la eficiencia y el control. De esta forma, estas agencias se aislan de los sistemas bajo manejo y se hacen mas inflexibles en su estructura. Simultaneamente y por medio de la sobrecapitalizacion, la sociedad se hace más dependiente del comando-y-control, demanda con mayores*

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intensidades e ignora los cambios ecológicos subyacentes o el colapso que se esta desarrollando. Las soluciones a esta patología no pueden provenir de un mayor comando-y-control (reglamentos), sino que deben provenir de estrategias innovativas que involucren incentivos que lleven a ecosistemas mas elasticos, agencias más flexibles, industrias más autosuficientes y una ciudadania más instruída. Discutimos varios aspectos del patrón y dinámica de los ecosistemas a gran escala que proveen una comprensión de la elasticidad del ecosistema y proponemos una "regla de oro" sobre el manejo de los recursos naturales, la cual creemos es necesaria para la sostenibilidad: El manejo debe esforzarse para retener los tipos y magnitudes de variación natural críticos en los sistemas de recursos a los efectos de mantener su elasticidad.

In ecology, we have an incredibly complex system with no central dogma like that of molecular biology to let us even pretend that we have control. Nowhere is this more apparent than in conservation, where we have persuaded ourselves that some degree of control is really necessary.

Ehrenfeld, 1991

An essential paradox of wilderness conservation is that we seek to preserve what must change.

Pickett and White, 1985

Introduction

Control is a deeply entrenched aspect of contemporary human societies: we control human behavior through laws, incentives, threats, contracts, and agreements; we control the effects of environmental variation by constructing safe dwellings; we control variation in our food resources by growing and storing agricultural products; we control human parasites and pathogens through good hygiene and medical technologies. All contribute to stable societies and human health and happiness, and within certain arenas this desire to control is undeniably to our individual and collective benefit. This approach to solving problems may be collectively referred to as "command and control," in which a problem is perceived and a solution for its control is developed and implemented. The expectation is that the solution is direct, appropriate, feasible, and effective over most relevant spatial and temporal scales. Most of all, command and control is expected to solve the problem either through control of the processes that lead to the problem (e.g., good hygiene to prevent disease, or laws that direct human behavior) or through amelioration of the problem after it occurs (e.g., pharmaceuticals to kill disease organisms, or prisons or other punishment of lawbreakers). The command-and-control approach implicitly assumes that the problem is well-bounded, clearly defined, relatively simple, and generally linear with respect to cause and effect. But when these same methods of control are applied to a complex, nonlinear, and poorly understood natural world, and when the same predictable outcomes are expected but rarely obtained, severe ecological, social, and economic repercussions result.

Humanity's contemporary interactions with nature are based on a mix of slowly developed social norms and expectations, and increasingly on more rapidly developed short-term incentives and controls. When the behaviors of people, institutions, or nature violate the norms, desires, or expectations of society, command and control is often sought as the primary solution in an effort to move human or ecosystem behaviors to a predetermined, predictable state. Consequently, much of natural resource management has been an effort to control nature in order to harvest its products, reduce its threats, and establish highly predictable outcomes for the short-term benefit of humanity. Our thesis is that adoption of such command and control has resulted in a pathology that permeates much of natural resource management and precludes long-term sustainability.

Command-and-Control Management

The command-and-control approach, when extended uncritically to treatment of natural resources, often results in unforeseen and undesirable consequences. A frequent, perhaps universal result of command and control as applied to natural resource management is reduction of the range of natural variation of systems—their structure, function, or both—in an attempt to increase their predictability or stability. That is, variation through time or space (such as system behavior over time, or spatial heterogeneity) is reduced. Thus, a common theme of many resource-management efforts is to reduce natural bounds of variation in ecological systems to make them more predictable, and thus more reliable, for human needs. We dampen extremes of ecosystem behavior or change species composition to attain a predictable flow of goods and services or to reduce destructive or undesirable behavior of those systems. For example, we control agricultural pests through herbicides and pesticides; we convert natural, multi-species, variable-aged forests into monoculture, single-aged plantations; we hunt and kill predators to produce a larger, more reliable supply of game species; we suppress fires and pest outbreaks in forests to ensure a steady lumber supply; we clear forests for pasture development and steady cattle production, and so forth.

Such efforts attempt to replace natural ecological controls, which are largely unknown to us and highly com-

plex and variable, with engineered constructs and manipulations that on the surface seem entirely within our control. The purpose is to turn an unpredictable and "inefficient" natural system into one that produces products in a predictable and economically efficient way. When unanticipated environmental problems then arise, the *a priori* expectation of certainty is not met and results in surprise and crisis—chemical pollution and erosion from monocultures, loss of biological diversity from tree farms, irruption of herbivore populations after predator removal, conflagrations and property loss when fires finally erupt, insect pest outbreaks when spraying stops, and pollution and erosion from grazing. Such crises and surprises, we argue here, are the *inevitable* consequences of a command-and-control approach to renewable resource management, where it is (implicitly or explicitly) believed that humans can select one component of a self-sustaining natural system and change it to a fundamentally different configuration in which the adjusted system remains in that new configuration indefinitely without other, related changes in the larger system.

We call the result "the pathology of natural resource management" (Holling 1986; Holling 1995), a simple but far-reaching observation defined here as follows: *when the range of natural variation in a system is reduced, the system loses resilience*. That is, a system in which natural levels of variation have been reduced through command-and-control activities will be less resilient than an unaltered system when subsequently faced with external perturbations, either of a natural (storms, fires, floods) or human-induced (social or institutional) origin. We believe this principle applies beyond ecosystems and is particularly relevant at the intersection of ecological, social, and economic systems.

Because much of our focus here is on loss of resilience, we must explore that concept further. Resilience of a system has been defined in two very different ways in the ecological literature; these differences in definition reflect which of two different aspects of stability are emphasized. The first definition, and the more traditional one, concentrates on stability near an equilibrium steady-state, where resistance to disturbance and speed of return to the equilibrium are used to measure resilience (Pimm 1984 &; O'Neill et al. 1986; Tilman & Downing 1994). We call that *equilibrium resilience*. The second definition, and the one of greater relevance here, emphasizes conditions far from any equilibrium in which instabilities can flip a system into another regime of behavior—to another stability domain (Holling 1973, 1994). In this case the measurement of resilience is the magnitude of disturbance that can be absorbed or accommodated before the system changes its structure by changing the variables and processes that control system behavior. We call that *ecosystem resilience* because its significance becomes clearly apparent for large-scale systems over long periods. The first definition focuses on efficiency, constancy, and predictability—attributes at the core of command-and-control desires for fail-safe design. The second focuses on persistence, change, and unpredictability—attributes embraced by an adaptive management philosophy. Holling (1973) first emphasized the consequences of these different definitions for ecological systems in order to draw attention to the paradoxes between constancy and change or between predictability and unpredictability.

The Pathology

For illustrative purposes we offer several examples of the pathology of natural resource management in which reduction of variation has led to a less resilient system, in the sense of ecosystem resilience:

(1) The loss of genetic variation in small populations is generally thought to result in a less resilient genetic system (Allendorf & Leary 1986; Meffe 1986), possibly resulting in higher probabilities of population extinction. This is particularly true if the environment changes and previously available genotypes that would be appropriate to the new environment no longer exist. Of course there are exceptions: for example, loss of deleterious recessive alleles is not likely to reduce population resilience and may in fact increase it. But overall, loss of genetic variance may lead to lower population resilience in ecological or evolutionary time.

(2) Stabilization of flows by dams in previously wildly flooding or "flashy" southwestern U.S. rivers results in a native fish fauna that is less resilient in the face of invasive fish species (Meffe 1984; Minckley & Meffe 1987). The high flow variation of unregulated rivers inhibits establishment of exotic fishes, and the last remaining strongholds of southwestern native riverine fishes are all in free-flowing rivers (Minckley & Deacon 1991). When flow variation is stabilized by dams and the process of violent flooding is removed, the resulting lentic conditions favorable to many exotic species allow them to flourish and eliminate native fishes that evolved with high flow variation. Stabilization of discharge variation and the presence of invasive species results in unresilient and declining native fish faunas.

(3) Suppression of fire in fire-prone ecosystems is remarkably successful in reducing the short-term probability of fire in the national parks of the United States and in fire-prone suburban regions. But the consequence is an accumulation of fuel over large areas that eventually produces fires of an intensity, extent, and human cost never before encountered (Kilgore 1976; Christensen et al. 1989). Fire suppression in systems that would frequently experience low-intensity fires results in the systems becoming severely affected by the huge fires that finally erupt; that is, the systems are not resilient to the major fires that occur with large fuel loads and may fun-

damentally change state after the fire. As this and the previous example serve to demonstrate, suppression or removal of a natural disturbance generally reduces system resilience.

(4) Monocultural, energy-intensive farming practices are the epitome of reduction of variation and loss of resilience. Plant species diversity in a natural forest converted to a monoculture may go from dozens or hundreds to one dominant, plus whatever weeds can escape the herbicides. Monocultures are notoriously susceptible to the effects of drought, flooding, insect or pathogen outbreaks, and market vagaries. They consequently require large inputs of energy (fertilizers, pesticides, herbicides, irrigation) and often large societal subsidies in the form of price supports, guaranteed loans, disaster relief, and surplus buyouts. These monocultures are fundamentally unresilient to natural or social perturbations.

(5) Natural, lateral flow variation (periodic floodplain inundation) throughout much of the Mississippi River drainage has been reduced by channelization and construction of a series of locks and levees to benefit agriculture, shipping, and floodplain development. As a result, the inextricably combined riverine-social system has little resilience during extreme storm events, as witnessed in the massive flooding of 1993. Attempted command-and-control of the river's flows, allowing expansive floodplain development, resulted in an unresilient riverine-social system and unprecedented economic destruction.

The same phenomenon applies equally well beyond natural resource management to many aspects of human existence. For example bureaucracies are an exercise in variance reduction through regulation and control; their purpose is elimination of extreme behavior through regulation to promote conformity to a specific set of standards, which to some degree is certainly desirable in a civilized society. But deeply entrenched bureaucracies are characteristically unresilient to new challenges because the system discourages innovation or other behavioral variance. This is clearly evidenced by merely presenting a unique situation to a clerk who has been narrowly trained in a highly standardized bureaucracy and watching the incredulous reply, or by the typically negative response to and occasional punishment of a government employee who offers an alternative perspective to the standard operating procedure.

The pathology of natural resource management involves not just a contraction of the resilience of ecosystems in response to human control: two other features make for an ultimate pathology. One feature concerns changes that occur in management agencies, and the other involves changes in economic sectors.

First, loss of ecosystem resilience is accompanied by changes in the management agencies. The initial phase of command and control is nearly always quite successful: insect pests are reduced by pesticide use; fishing and hunting are enhanced by stocking or predator removal; forest fires are suppressed for years; floods are minimized by levees. As a consequence, agencies responsible for management shift their attention from the original social or economic purpose to an otherwise laudable effort to increase efficiency and reduce costs—better and more efficient ways to kill insects, eliminate wolves, rear hatchery fish, detect and extinguish fires, or control flows. Priorities thus shift from research and monitoring (why "waste" money studying and monitoring apparent success?) to internal agency goals of cost efficiency and institutional survival. The second feature of the pathology thus emerges: growing isolation of agency personnel from the systems being managed and insensitivity to public signals of concern—in short, growing institutional myopia and rigidity.

At the same time, economic activities exploiting the resource benefit from success and expand in the short term, and we witness greater capital investment in activities such as agricultural production, pulp mills, suburban development, and fishing and hunting. That too is laudable within limits: it is the development of human opportunity and enterprise. But the result is increasing dependency on continued success in controlling nature while, unknown to most, nature itself is losing resilience and increasing the likelihood of unexpected events and eventual system failure. With dependency comes denial, demands by economic interests to keep and expand subsidies, and pressure for further command and control. This third feature provides the final element to the ultimate pathology of command-and-control resource and environmental management. The composite result is increasingly less resilient and more vulnerable ecosystems, more myopic and rigid institutions, and more dependent and selfish economic interests all attempting to maintain short-term success.

If the response to this pathology by other interests, such as the environmental community, is exclusively demand for tighter regulation and prohibition, then the pathology is deepened, because this applies a command-and-control solution to a problem initiated by command and control. The result is that lobby groups battle other lobby groups and generate the gridlocks and train wrecks that are now regional issues—from salmon, owls, fishing, and logging in the Pacific Northwest, to cod, poverty, and cultural survival in Newfoundland, to sugar, urbanization, wildlife, and water in the Everglades (Gunderson et al. 1995).

Such problems, with a complex of causes, do not have simple solutions. We know the goal: more resilient ecosystems, more flexible agencies, more self-reliant industries, and more knowledgeable citizens. We also know the ingredients of the solution, if not the specific ways to combine and use those ingredients. First, replace economic subsidies with incentives designed so that restoration and maintenance of ecosystem resilience is to the

benefit of economic enterprise. An example is the conservation policies that reward farmers for restoration of habitat and soils. Second, develop ways for agencies to innovate and learn, and allow them to do so. An example is the application of actively adaptive environment management approaches, where policies become hypotheses and management actions become the experiments to test those hypotheses (Holling 1978; Walters 1986; Lee 1993; Gunderson et al. 1995). Third, engage people as active partners in the process of science and policy. Examples are the various regional and continental monitoring schemes by which people monitor changes in nature—acid rain in the northeast, bird populations along flyways, water quality in bays and rivers. Monitoring of ecological change over time and space is critical to a better understanding of our managed resource systems and must be a central component of any adaptive management scenario. Monitoring provides the data for the management experiment and the basis for deciding the success or failure of the approach. Fourth, develop local partnerships among broad constituencies that all stand to gain (or lose) together from good (or poor) resource management.

The Behavior of Natural Ecosystems

Our suggestions would be more effective with a better understanding of ecosystem behavior, structure, and dynamics at all spatial scales from the plant to the planet and at all temporal scales from seconds to millennia. The surprises and crises created by the pathology are not only the consequence of incomplete knowledge of how to control nature's variability or improper controls being applied. They also include ignorance of the *constructive* role that variation plays in maintaining the integrity of ecosystem function in the face of unexpected events. Recently, a group of ecologists working with large-scale terrestrial, fresh-water, and marine ecosystems developed a synthesis of their experience with natural, disturbed, and managed ecosystems (Holling et al. 1995). They identified key features of ecosystem structure and dynamics that explain why surprise and crisis are an inevitable outcome of command-and-control approaches. They concluded with the following lessons:

(1) Ecological change is not continuous and gradual; rather, it is episodic, with slow accumulation of natural capital such as biomass or nutrients, punctuated by sudden releases and reorganization of that capital as the result of internal or external natural processes or of human imposed catastrophes. Rare events, such as hurricanes or the arrival of invading species, can unpredictably shape structure at critical times or at locations of increased vulnerability; the effects of these rare events can persist for very long periods. Therein lies one of the sources of new options that environmental diversity and variation provide. Irreversible or slowly reversible states exist; once the system flips into such a state, only explicit management intervention can restore its previous self-sustaining state, and even then success is not assured (Walker 1981). *Conclusion: Critical processes function at radically different rates and at spatial scales covering several orders of magnitude, and these rates and scales cluster around a few dominant frequencies.*

(2) Spatial attributes are not uniform or scale-invariant. Rather, productivity and textures are patchy and discontinuous at all scales, from the leaf to the individual to the vegetation patch to the landscape to the planet. There are several different ranges of scales, each with different attributes of patchiness and texture (Holling 1992). *Conclusion: Scaling up from small to large cannot be a process of simple linear addition: non-linear processes organize the shift from one range of scales to another. Not only do the large and slow control the small and fast, the latter occasionally "revolt" to affect the former.*

(3) Ecosystems do not have single equilibria, with functions controlled to remain near them. Rather, multiple equilibria, destabilizing forces far from equilibria, and absence of equilibria define functionally different stable states, and movement between states maintains an overall structure and diversity. *Conclusion: On the one hand, destabilizing forces are important in maintaining diversity, resilience, and opportunity. On the other hand, stabilizing forces are important in maintaining productivity and biogeochemical cycles, and, even when these features are perturbed, they recover rapidly if the stability domain is not exceeded (e.g., recovery of lakes from eutrophication or acidification; Schindler 1990; Schindler et al. 1991).*

(4) Policies and management that apply fixed rules for achieving constant yields independent of scale (e.g., constant carrying capacity of cattle or wildlife or constant sustainable yield of fish, wood, or water) lead to systems that gradually lose resilience—systems that suddenly break down in the face of disturbances that previously could be absorbed (Holling 1986). *Conclusion: Ecosystems are moving targets, with multiple potential futures that are uncertain and unpredictable. Therefore management has to be flexible, adaptive, and experimental at scales compatible with the scales of critical ecosystem functions (Holling 1978; Walters 1986; Lee 1993; Gunderson et al. 1995).*

A Closer Look at Resilience

The features we have discussed are the consequences of the stabilizing properties of natural ecosystems. In the ecological literature these properties have been given focus through debates on the meaning and reality of the resilience of ecosystems.

Earlier, we briefly defined resilience in two ways. These two aspects of a system's stability have very different consequences for evaluating, understanding, and managing complexity and change. Ecosystem resilience, our preferred definition, focuses on the interplay between stabilizing and destabilizing properties, which are at the heart of present issues of development and the environment: global change, biodiversity loss, ecosystem restoration, and sustainable development. Nevertheless, much of present ecological theory uses the equilibrium definition of resilience, even though that definition reinforces the pathology of equilibrium-centered command and control. That is because much of that theory draws predominantly from traditions of deductive mathematical theory (Pimm 1984) in which simplified, untouched ecological systems are imagined, or from traditions of engineering in which the motive is to design systems with a single operating objective (Waide & Webster 1976; De Angelis et. al. 1980; O'Neill et al. 1986), or from small-scale quadrat experiments in nature (Tilman & Downing 1994) in which long-term, large-scale successional or episodic transformations are not of concern. That makes the mathematics more tractable, it accommodates the engineer's goal to develop optimal designs, and it provides the ecologist with a rationale for utilizing manageable, small sized, and short-term experiments, all reasonable goals. But these traditional concepts and techniques make the world appear more simple, tractable, and manageable than it really is. They carry an implicit assumption that there is global stability—that there is only one equilibrium steady-state, or, if other operating states exist, they should be avoided with safeguards and regulatory controls. They transfer the command-and-control myopia of exploitive development to similarly myopic demands for environmental regulations and prohibitions.

Those who emphasize ecosystem resilience, on the other hand, come from traditions of applied mathematics and applied resource ecology at the scale of ecosystems, such as the dynamics and management of freshwater systems (Fiering 1982), forests (Clark et al. 1979), fisheries (Walters 1986), semiarid grasslands (Walker et al. 1969), and interacting populations in nature (Dublin et al. 1990; Sinclair et al. 1990). Because these studies are rooted in inductive rather than deductive theory formation and in experience with the effects of large-scale management disturbances, the reality of flips from one stable state to another cannot be avoided (Holling 1986). Indeed, management and resource exploitation can overload waters with nutrients, turn forests into grasslands, trigger collapses in fisheries, and transform savannas into shrub-dominated semideserts.

These two different views of resilience reflect two different traditions of ecological science: that of equilibrium resilience is experimental, analytical, and focuses on small spatial scales and short durations; that of ecosystem resilience is integrative, synthetic, and focuses on multiple scales. The consequences lead not only to opposite views of system behavior but to opposite views of system structure that have major consequences for policy. For example, there is a debate over whether every species is important in ecosystem dynamics and function or whether only a smaller subset is involved in self-organization (Baskin 1994). On the one side is evidence from controlled experiments showing that declining generalized diversity reduces productivity (Naeem et al. 1994), or that reducing numbers of grass species reduces rates of recovery from drought (Tilman & Downing 1994). In such examples, however, the physical limitations of the experiments limit the conclusions to small-scale interactions (plots ranged 1–4 m on a side) over short periods and to the set of structuring species that happened to be selected at those scales. In contrast, those who argue that a subset of species control dynamics and function draw their evidence from large-scale manipulations of whole ecosystems such as lakes (Schindler 1990), from an understanding of process function at different scales (Holling 1992; Levin 1992), from landscape- and ecosystem-scale models (Clark et al. 1979; Costanza et al. 1986; Walters & Gunderson 1994), and from field measures of disturbed and managed ecosystems (Hughes 1994). These observations address boreal, marine, freshwater, and savanna ecosystems and indicate that functional diversity is determined not by all species but by species involved in a set of structuring processes (Schindler 1990; Holling et al. 1995). Examples include the set of grass species and ungulate grazers that maintain the productivity and resilience of savannas (Walker et al. 1969) and the tree species and suite of 35 species of insectivorous birds that mediate budworm outbreak dynamics in the eastern boreal forest (Holling 1988).

Any ecosystem contains hundreds to thousands of species interacting among themselves and their physical and chemical environment. But not all those interactions have the same strength or the same direction. That is, although everything might ultimately be connected to everything else if the web of connections is followed far enough, the first-order interactions that structure the system increasingly seem to be confined to a subset of biotic and abiotic variables whose interactions form the "template" (Southwood 1977) or the niches that allow a great diversity of living things to, in a sense, "go along for the ride" (Carpenter & Leavitt 1991; Cohen 1991; Holling 1992). Those species are affected by the ecosystem but do not, in turn, notably affect the ecosystem, at least in ways that our relatively crude methods of measurement can detect. At the extremes, therefore, species can be regarded either as "drivers" or as "passengers" (Walker 1992), although this distinction needs to be treated cautiously. The driver role of a species may become apparent only every now and then under particular conditions that trigger their key structuring function.

This large-scale view of ecosystems highlights where the priority for resource management, ecosystem restoration, or biodiversity policy should lie. Ecological change is not incremental and local but sudden and extensive. If change does occur, there may be fundamental transformations from one ecosystem type to another—from forest to grassland or grassland to a shrubby semidesert, for example (Walker et al. 1969; Holling 1973). Then control of structure will shift from one set of organizing processes and variables to another. It is the diversity of overlapping influences within those controls that defines the resilience to those sudden shifts.

The fundamental points are that only a small set of self-organizing processes made up of biotic and physical elements are critical in forming the structure and overall behavior of ecosystems, and that these establish sets of relationships, each of which dominates over a definable range of scales in space and time. Each set includes several species of plants or animals, each species having similar but overlapping influence to give functional redundancy. It is that set, operating with abiotic processes, that generates and maintains ecosystem resilience. It provides the focus for identifying the types and sources of variation that are critical for maintaining the integrity of a natural system.

Thus, we suggest that an ecosystem-resilience perspective better reflects the reality of large-scale processes and dynamics and provides the most realistic foundation for addressing the challenging and complex resource mangement issues of the day. It also provides the conceptual basis necessary to appreciate and understand the paradoxes typically encountered in resource management, as well as the pathology we describe here.

A Golden Rule for Natural Resource Management

The various observations presented herein suggest a "Golden Rule" of natural resource management: *Natural resource management should strive to retain critical types and ranges of natural variation in ecosystems.* That is, management should *facilitate* existing processes and variabilities rather than changing or controlling them. By so doing, ecosystem resilience and the organizing processes and structures of ecosystems will be maintained, thus better serving not only the natural functions and species diversity of those systems but also the long-term (although not necessarily short-term) interests of humanity. This is a more sophisticated way of stating Aldo Leopold's (1949) famous assertion that "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise." Because we know more today about the dynamics of ecological communities than Leopold did in the 1940s, we would replace "stability" with "resilience;" otherwise, this remains sound advice, and Leopold clearly anticipated the pathology of natural resource management as elaborated here.

We fully recognize that the particular "rule" we propose has far greater conceptual than prescriptive power. Prescriptions and cookbook approaches generally should be avoided in conservation (Meffe & Carroll 1994), if for no other reason than the systems with which we work are idiosyncratic and endlessly varied. No single, detailed prescription can be of much use for more than a single system. Furthermore, our rule is operationally vague. What is a "critical type" or a "critical range" of variation? That, obviously, is specific to a system and is often not known with any degree of assurance. Ehrenfeld (1992) indicated that "...it is extremely difficult to determine a normal state for communities whose parameters are often in a condition of flux because of natural disturbance." Schindler (1987) further explained that "...we usually do not know the normal range for any variable, at least for any time period greater than a few years."

Thus, our advice to "retain critical types and ranges of natural variation" must remain for the present as a management goal to which to aspire, as a conceptual underpinning for management, rather than an operational dictum. In practice this translates to adopting a conservative approach to changing parameters of systems we understand poorly but that we wish to manage. It means that the default condition, unless clearly proven otherwise, should be retention of the natural state rather than manipulation of system components or dynamics. It argues for humility when managing large systems (Stanley 1995). It shifts the burden of proof from managing by system manipulation to managing by minimal intervention, unless proven otherwise. It also argues strongly for adaptive management rather than command-and-control prescriptions, and development of consistent and dedicated monitoring of systems, both natural and managed. Only through long-term data collection can we begin to close the knowledge gap in understanding normal system behavior, particularly its variance.

How would this Golden Rule, at least in concept, modify resource management practices to take into account the pathology of natural resource management? We revisit our earlier examples and indicate how resource management might be altered to adhere to the Golden Rule:

(1) Genetic diversity of small populations should be retained and not further eroded by management practices (Schonewald-Cox et al. 1983; Falk & Holsinger 1991). This includes maintenance of natural gene flow in the wild (Meffe & Vrijenhoek 1988), reserves large enough to maintain large breeding populations or metapopulations of species of concern, and avoidance of population crashes, bottlenecks, or inbreeding in captive breeding programs.

(2) In riverine systems with naturally high variation in discharge, replace stabilization of flows via dams with

watershed restoration and protection. Begin to remove dams to restore the critical ecosystem process of discharge variation. Price water to accurately reflect its ecosystem value in order to stimulate conservation measures, and remove flood-prone lands from development. Combine this with a bioregional perspective that matches development practices to natural, regional ecological constraints. Develop a combination of regional and national incentives and disincentives that would eliminate ecologically disastrous development such as large desert cities that rely on water from far outside of the region and mining of fossil water with a temporally limited productive capacity.

(3) Eliminate policies of fire suppression in naturally fire-prone ecosystems. Eliminate incentives that encourage rebuilding in such ecosystems after fire destruction, and develop incentives such as tax reductions to site new housing and other developments away from such areas, eventually to be designated as wilderness.

(4) Proceed from simple monocultures to more complex agroecosystems with integrated pest management and no-till methods (Carroll et al. 1990). Promote, though education and economic means, ecological complexity in agriculture, eliminating as much as possible energetic and societal subsidies, allowing free ecosystem services (e.g., diversity of predators on pests, soil conservation through no-till methods) to support agriculture.

(5) Relocate communities out of floodplains of the Mississippi River and other large riverine systems; use those areas as wildlife refuges and corridors and as natural buffers and recharge zones for agroecosystems (as is now being promoted in some parts of the Mississippi floodplain). Provide disincentives for further floodplain development.

(6) Examine bureaucracies to identify underlying reasons for their general intransigence and brittleness, and promote incentives for alternative behaviors. Develop incentives and rewards for innovation that place streamlining, local solutions, and concern for customers and sustainability above adherence to a command structure.

Conclusions

Rather than pursuing short-term gain through command and control, effective natural resource management that promotes long-term system viability must be based on an understanding of the key processes that structure and drive ecosystems, and on acceptance of both the natural ranges of ecosystem variation and the constraints of that variation for long-term success and sustainability. This is especially urgent when the growth of the human population and its consumption of resources is added to the picture, as it always must be (Meffe et al. 1993). Despite our penchant to control so many systems through command-and-control techniques, with a few conspicuous exceptions the underlying problem of population growth is often ignored. Ironically, our attempts at command and control are usually directed at complex, poorly understood, and nonlinear natural systems, rather than at the fundamental source of the problem—human population growth and consumption—where control is viable, reasonable, and could be effective. A rapidly increasing human population and increasing consumption is resulting in greater demands on and competition for dwindling and increasingly damaged natural resources. The resource problems we encounter today can only multiply as the human population grows, which means that the errors of command and control will be compounded, which will only lead to calls for more command and control by those who do not fundamentally understand the pathology outlined herein. This highlights the urgency of quickly changing our fundamental approaches to natural resource management and developing solutions and appropriate models of management behavior while time and resources still permit.

Command-and-control management can lead to short-term economic returns, but it also increases the vulnerability of ecosystems to perturbations that otherwise could be absorbed. Any move toward truly sustainable human endeavors must incorporate this principle or it cannot succeed. Our observations are also pertinent to the present move toward ecosystem management in the United States and elsewhere. If ecosystem management is to be more than another buzzword, then there is no substitute for understanding the structure and dynamics of natural ecosystems over spatial and temporal scales covering several orders of magnitude. The role of variation in structuring ecosystems and maintaining their resilience, and managing within the constraints of that structure and dynamics, is critical. We must also modify our institutions and policies to recognize the pathology described herein and to root out similar pathologies in institutional and policy behaviors. To ignore this is to perpeturate the pathology of natural resource management and place ecosystems and humanity at great risk.

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Literature Cited

Allendorf, F. W., and R. F. Leary. 1986. Heterozygosity and fitness in natural populations of animals. Pages 57–76 in M. E. Soulé, editor. Conservation biology: The science of scarcity and diversity. Sinauer Associates, Sunderland, Massachusetts.

Baskin, Y. 1994. Ecologists dare to ask: How much does diversity matter? Science **264**:202–203.

Carpenter, S. R., and P. R. Leavitt. 1991. Temporal variation in paleolimnological record arising from a trophic cascade Ecology **72**: 277–285.

Carroll, C. R., J. H. Vandermeer, and P. M. Rosset, editors 1990. Agroecology. McGraw-Hill, New York.

Christensen, N. L., et al. 1989. Interpreting the Yellowstone fires of 1988. BioScience **39**:678–685.

Clark, W. C., D. D. Jones, and C. S. Holling. 1979. Lessons for ecological policy design: A case study of ecosystem management Ecological Modeling **7**:1–53.

Cohen, J. 1991. Tropic topology. Science **251**:686–687.

Costanza, R., F. H. Sklar, and J. W. Day, Jr. 1986. Modeling spatial and temporal succession in the Atchafalaya/Terrebonne marsh/estuarine complex in South Louisiana. Pages 387–404 in D. A. Wolfe, editor. Estuarine variability. Academic Press, New York.

DeAngelis, D. L., W. M. Post, and C. C Travis. 1980. Positive feedback in natural systems. Springer-Verlag, New York.

Dublin, H. T., A. R. E. Sinclair, and J. McGlade. 1990. Elephants and fire as causes of multiple stable states in the Serengeti-mara woodlands Journal of Animal Ecology **59**:1147–1164.

Ehrenfeld, D. 1991. The management of diversity: a conservation paradox. Pages 26–39 in F. H. Borman and S. R. Kellert, editors Ecology, economics, ethics: the broken circle. Yale University Press, New Haven, Connecticut.

Ehrenfeld D. 1992. Ecosystem health and ecological theories. Pages 135–143 in R. Costanza, B. G. Norton, and B. D. Haskell, editors Ecosystem health: New goals for environmental management Island Press, Covelo, California.

Falk, D. A., and K. E. Holsinger. 1991. Genetics and conservation of rare plants. Oxford University Press, New York.

Fiering, M. B. 1982. A screening model to quantify resilience. Water Resources Research **18**:27–32.

Gunderson, L., C. S. Holling, and S. Light, editors. 1995. Barriers and bridges to the renewal of ecosystems and institutions. Columbia University Press, New York.

Holling, C. S. 1973. Resilience and stability of ecology systems. Annual Review of Ecology and Systematics **4**:1–23

Holling, C. S. 1978. Adaptive environmental assessment and management. John Wiley and Sons, New York.

Holling, C. S. 1986. The resilience of terrestrial ecosystems, local surprise and global change. Pages 292–317 in W. C. Clark and R. E. Munn, editors. Sustainable development of the biosphere Cambridge University Press, Cambridge.

Holling, C. S. 1988. Temperate forest insect outbreaks, tropical deforestation and migratory birds. Memoirs of the Entomological Society of Canada **146**:21–32.

Holling, C. S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Ecological Monographs **62**:447–502.

Holling, C. S. 1994. New science and new investments for a sustainable biosphere. Pages 57–73 in A. M. Jansson, M. Hammer, C. Folke and R. Costanza, editors. Investing in natural capital. Island Press, Washington, D.C.

Holling, C. S. 1995. What barriers? What bridges? Pages 3–34 in L. H. Gunderson, C. S. Holling, and S. S. Light, editors. Barriers and bridges to the renewal of ecosystems and institutions. Columbia University Press, New York.

Holling, C. S., D. W. Schindler, B. W. Walker, and J. Roughgarden. 1995. Biodiversity in the functioning of ecosystems: An ecological primer and synthesis. Pages 44–83 in C. Perrings, K. G. Maler, C. Folke, B. O. Jansson and C. S Holling, editors. Biodiversity loss: ecological and economics issues. Cambridge University Press, New York.

Hughes, T P. 1994. Catastrophes, phase shifts and large scale degradation of a Caribbean Coral Reef Science **265**:1547–1551.

Kilgore, B. M. 1976. Fire management in the natural parks: an overview. Pages 45–57 in Proceedings of Tall Timbers fire ecology conference Florida State University Research Council, Tallahassee.

Lee, K. N. 1993. Compass and gyroscope: Integrating science and politics for the environment Island Press, Covelo, California.

Leopold, A. 1949. A Sand County almanac and sketches here and there. Oxford University Press, New York.

Levin, S. A 1992 The problem of pattern and scale in ecology. Ecology **73**:1943–1967.

Meffe, G. K. 1984. Effects of abiotic disturbance on coexistence of predator-prey fish species. Ecology **65**:1525–1534.

Meffe, G. K. 1986. Conservation genetics and the management of endangered fishes. Fisheries **11**:14–23.

Meffe, G. K., and C. R Carroll. 1994. Principles of conservation biology. Sinauer Associates, Sunderland, Massachusetts.

Meffe, G. K., and R. C. Vrigenhoek. 1988. Conservation genetics in the management of desert fishes. Conservation Biology **2**:157–169.

Meffe, G. K., A. H. Ehrlich, and D Ehrenfeld. 1993. Human population control: the missing agenda. Conservation Biology **7**:1–3.

Minckley, W. L., and J. E. Deacon, editors. 1991 Battle against extinction Native fish management in the American West. University of Arizona Press, Tucson.

Minckley, W. L., and G. K. Meffe 1987. Differential selection by flooding in stream-fish communities of the arid American Southwest Pages 93–104 in D. C. Heins and W. J. Matthews, editors. Evolutionary and community ecology of North American stream fishes University of Oklahoma Press, Norman.

Naeem, S., L. J Thompson, S. P Lawler, J. H. Lawton, and R. M. Woodfin 1994. Declining biodiversity can alter the performance of ecosystems. Nature **368**:734–737.

O'Neill, R. V , D. L DeAngelis, J. B. Waide, T. F H. Allen. 1986. A hierarchical concept of ecosystems Princeton University Press, Princeton, New Jersey.

Pickett, S. T. A., and P. S. White, editors. 1985. The ecology of natural disturbance and patch dynamics Academic Press, Orlando, Florida.

Pimm, S L. 1984. The complexity and stability of ecosystems. Nature **307**:321–326.

Schindler, D. W. 1987. Detecting ecosystem responses to anthropogenic stress. Canadian Journal of Fisheries and Aquatic Sciences **44**(suppl 1):6–25.

Schindler, D. W. 1990. Experimental perturbations of whole lakes as tests of hypotheses concerning ecosystem structure and function. Oikos **57**:25–41.

Schindler, D. W , et al. 1991 Freshwater acidification, reversibility and recovery: Comparisons of experimental and atmospherically-acidified lakes. Pages 193–226 in F. T. Last and R. Watling, editors. Acidic deposition: its nature and impacts. Proceedings of the Royal Society of Edinburgh, Edinburgh.

Schonewald-Cox, C. M., S. M. Chambers, B. MacBryde, and L. Thomas, editors. 1983. Genetics and conservation: A reference for managing wild animal and plant populations. Benjamin/Cummings, Menlo Park, California.

Sinclair, A. R. E., P. D. Olsen, and T. D. Redhead. 1990. Can predators regulate small mammal populations? Oikos **59**:382–392.

Southwood, T. R. E. 1977. Habitat, the template for ecological strategies? Journal of Animal Ecology **46**:337–365.

Stanley, T. R., Jr. 1995 Ecosystem management and the arrogance of humanism. Conservation Biology **9**:255–262.

Tilman, D., and J. A. Downing. 1994. Biodiversity and stability in grasslands. Nature **367**:363–365.

Waide, J. B., and J R. Webster. 1976. Engineering systems analysis. applicability to ecosystems. Pages 329–372 in B. C. Patton, editor. Systems analysis and simulation in ecology. Academic Press, New York.

Walker, B. H. 1981. Is succession a viable concept in African savanna ecosystems? Pages 431–447 in D. C. West, H. H. Shugart, and D. B Botkin, editors. Forest succession: concepts and application. Springer-Verlag, New York.

Walker, B. H., 1992. Biological diversity and ecological redundancy Conservation Biology **6**:18–23.

Walker, B. H., D. Ludwig, C. S. Holling, and R. M. Peterman 1969. Stability of semi-arid savanna grazing systems Journal of Ecology **69**: 473–498.

Walters, C. J. 1986. Adaptive management of renewable resources McGraw Hill, New York.

Walters, C., and L. Gunderson 1994. A screening of water policy alternatives for ecological restoration in the Everglades. Pages 757–767 in S. M. Davis and J. Ogden, editors. Everglades: the ecosystem and its restoration. St Lucie Press, Delray Beach, Florida.