ISSUE BRIEF

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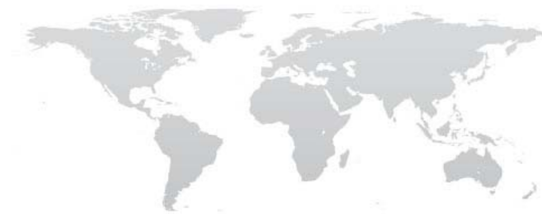
RESOURCES FOR THE FUTURE

July 2010
Issue Brief 10-16

Resources for the Future



Ecosystem Services and Climate Adaptation

James Boyd[1]

As defined by the Intergovernmental Panel on Climate Change, adaptation includes a set of actions to moderate harm or exploit beneficial opportunities in response to climate change. To date, little research has addressed public policy options to frame the nation's approach to adapt to a changing climate. In light of scientific evidence of extreme and unpredictable climate change, prudent policy requires consideration of what to do if markets and people fail to anticipate these changes, or are constrained in their ability to react. This issue brief is one in a series that results from the second phase of a domestic adaptation research project conducted by Resources for the Future. The briefs are primarily intended for use by decisionmakers in confronting the complex and difficult task of effectively adapting the United States to climate change impacts, but may also offer insight and value to scholars and the general public. *This research was supported by a grant from the Smith-Richardson Foundation.*

Policy Recommendations

Natural resources and ecological systems are a significant source of economic wealth. Climate change will have many adverse impacts on natural systems and the wealth they generate, but how and to what extent these impacts manifest themselves is uncertain. Additionally, ecosystem goods and services are more difficult to price than conventional goods. The U.S. government can pursue the following strategies, however, to help protect and adapt ecological goods and services to changing climatic conditions:

- Increase investment in research in evidence-based ecology to better understand biophysical production functions and measure the economic value of ecological goods and services.
- Employ hedging strategies to manage the resilience of ecosystems as insurance against costly reductions in the supply of ecosystem goods and services.

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- Acknowledge the economic option value associated with ecological protection—that is, the value of girding natural systems against climate impacts and delaying uncertain and irreversible damage to biophysical systems until biophysical and economic uncertainties are resolved.
- Develop portfolio approaches that value and restore multiple complementary ecological functions and goods.

Introduction

Nature's ecosystem goods and services often are not traded in markets and thus lack observable prices, but they are the foundation on which economic activity and social welfare depend. Broadly, ecosystem goods and services refer to the dependence of economic wealth and human well-being on natural systems. The relationship between changes in natural systems and corresponding changes in human welfare is today a focus of both ecology and economics (Daily 1997; Wainger et al. 2001; Ricketts et al. 2004; Polasky et al. 2005; Boyd 2006; Carpenter et al. 2006; Boyd and Banzhaf 2007; Barbier et al. 2008).

Preservation and management of natural wealth—including clean air; clean, plentiful water; productive soils; and plant and animal species—are important policy goals even in the absence of climate change. Environmental stresses from land development, water demands, air pollution, and harvests of marine and other species in some cases threaten ecological wealth. Examples include degradation of water quality from agricultural and developed land uses, loss of habitat and species abundance as land cover is modified or water is diverted to urban and agricultural use, and depletion of species from overharvesting. Analysis of ecosystem goods and services attempts to make these ecological changes—and their economic implications—visible to decisionmakers.

Climate change poses daunting new challenges because it will alter the amount and locations of wealth produced by natural systems. Adapting to climate change will involve the protection and management of natural wealth as it changes or is threatened by climate change.

This brief focuses on two broad questions. First, what kinds of adaptation challenges will be created by climate-driven changes in the form, scale, and location of ecosystem goods and services? Climate change will alter natural systems and thus lead to a new "portfolio" of natural wealth. In some cases, climate change may increase the productivity of certain natural systems (i.e., through longer growing seasons in the northern plains of the United States). Often, however, the opposite will be true, as water becomes scarce, land is flooded, and species habitat disappears. In all cases, the location of natural wealth is likely to migrate in unpredictable ways.

These biophysical changes can and should be viewed as economic impacts to which we will have to adapt.

Moreover, altered natural systems will lead to social change. Commercial and agricultural production, populations, and land development will themselves migrate in response to changes in the natural world. These migrations will create feedbacks of their own, since the changed human footprint will place new stresses on natural systems. In other words, ecosystem goods and services will both drive social adaptation and become stressed by that adaptation.

The second question addressed by this brief is how climate adaptation policies should protect and manage natural wealth as its delivery is affected by climate change. A range of adaptation policies are available, from investments in resource protection, land use regulation, sequestration incentives, cap-and-trade policies, pricing of natural resources, and tax incentives.

For all these options, two broad features of the problem are particularly important. The first challenge is the geographic movement of natural wealth over time. Policy approaches that assume static natural resource conditions will lead to ecologically inappropriate and economically costly interventions.

The second challenge is the inherent difficulty of measuring natural wealth. Wealth management requires biophysical measurement that can be translated into economic terms. For reasons that will be explained below, this challenge requires significant investment in biophysical and economic assessment of natural systems. Our current ability to track changes in the natural economy does not match our ability to track changes in the market economy.

Biophysical Change Will Lead to Changes in the "Natural Economy"

In Phase I of this project, ecologists (Covich 2009; Running and Mills 2009) describe climate-related physical changes (precipitation, temperature, and water availability) and how they are likely to affect biological conditions, given that biological systems will adapt to physical change and stress. The biophysical changes described in such analyses are not just ecologically important. They are economically important, as well.

Any biophysical change in delivery of ecosystem goods and services creates a corresponding economic change. For example, water scarcity implies either reduced economic production by agriculture, industry, and households or costly attempts to find more water by, for instance, drilling deeper wells. Stronger storm activity and more frequent forest fires imply larger damages to private and public property. Climate impacts on species' habitat and abundance will change commercial and subsistence harvests and recreational, aesthetic, and spiritual well-being. Most natural resources or ecological systems can be described as inputs to bundles of economically valuable outputs. Rarely does a particular species or patch of landscape provide just one economic benefit.

Biophysical change and adaptation will have a wide range of economic and social impacts. Consider two examples. First, reduced snowpack in the Sierra Nevada due to climate change will trigger such economic impacts as reduced agricultural productivity in the Central Valley, municipal consumption restrictions, and reduced boating and skiing opportunities. Its ecological impacts will include disruptions of several fish species' breeding and foraging behavior, affecting inland and marine fish stocks dependent on the Sacramento Bay Delta. Second, coastal wetlands provide necessary habitat to marine species that are commercially, recreationally, or ethically valuable; buffer inland groundwater supplies from saltwater intrusion; and protect against storm surges and flooding. If damaged, communities may be exposed to flood damages.

Economic changes brought about by changed delivery of natural wealth may in turn have profound demographic impacts. The location of human populations, commerce, and agriculture are closely linked to natural resource availability. Most obviously, the location of agriculture depends on favorable soil, water, and temperature conditions. The location of towns and cities in proximity to surface water for power and transportation needs is another clear example. Even economic activity that does not directly depend on natural resources is affected because, for example, workers prefer to live and work in locations with environmental amenities, including clean air and water.

Thus, as ecological goods and services "move" in response to climate change, human activity will move with them. The location of agriculture, recreation, housing, and manufacturing will all change. Resettlement will impose a variety of costs, including the costs of new infrastructure to service shifting populations (see Neumann 2009). Existing infrastructure investments, including those for dams and reservoirs, may be stranded as economic activity moves.

Setting those costs aside, shifting demography will place additional stress on ecosystem goods and services and thus create new resource scarcities (and costs). The conversion of land to developed uses will lead to the same kinds of water, soil, habitat, and air quality threats experienced in today's developed areas.

Management of Ecosystem Goods and Services in a "Static" Scenario

Before turning to the policy challenges associated with climate adaptation, consider the management of ecological wealth in a "static" scenario, where climate is not changing.[2] As we will argue, our ability to measure and manage ecological wealth with precision is limited, even

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[2] Natural and economic systems are never static. We use the term simply to distinguish the "with" and "without" climate change scenarios.

without the complications of climate change. This in turn will have important implications for adaptation-oriented policies. The assessment and management of ecosystem services involves two broad missions, one biophysical the other economic.

THE BIOPHYSICAL AGENDA

The biophysical mission is associated with ecology, hydrology, and the other natural sciences. Natural science is needed to answer the following questions: How can we manage, protect, or enhance biophysical goods and services? If we want clean air and water, healthy and abundant species populations, pollination, irrigation, and protection from floods and fires, how can we take action to preserve these things? If nature can be thought of as a factory that produces many outputs, then the natural sciences' mission is to describe the production of ecological outputs.

Because environmental features and qualities are fundamental to our economic welfare and well-being, they are a natural focus for economic assessment and concern. Ecological concerns about damage to systems, species, and functions are mirrored by economic concerns, since our welfare depends on the outputs and qualities of ecological systems. Of great interest to both ecology and economics are the *biophysical production functions* that govern natural systems and, in particular, govern the production of ecosystem goods and services (Boyd 2007; Daily and Matson 2008; U.S. EPA 2009).

In conventional economic terminology, production functions describe the manner in which an output is related to the quantity and nature of inputs used to create it. For example, a production function describes the way in which a company can deploy labor and capital investments to manufacture a final product. Ecological analysis is concerned with the biological, chemical, and hydrological relationships that determine biological production.[3] An ecosystem's structure, such as size, vegetation, and boundaries, and its functional aspects, such as ability to absorb floodwater or remove contaminants from surface water, are biophysical contributors—as inputs—to the services the habitat generates.

The challenge for the natural sciences concerned with adaptation is to empirically demonstrate cause-and-effect relationships when biophysical "inputs" and "processes" are altered by climate change and subsequently yield ecological "outputs" that are better, worse, or different. Unfortunately for the analyst of natural wealth, biophysical systems are complex; composed of many features, things, and qualities that interact with other physical features, things, and qualities; and are changed via physical processes. These natural processes convert inputs—some natural, some man-made—into outputs, such as air quality and species populations.

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[3] Agricultural and natural resource economics also have a long history of integrated economic and biological production function analysis. Among other things, agricultural studies show how substitution of one farm input for another (e.g., land for fertilizer, tractors for man-hours) affects production levels, or how landscape characteristics affect yields. For a general overview, see *Introduction to Agricultural Economics,* edited by John Penson et al. Prentice Hall, 1999.

Even in a world without climate change, our understanding of these biophysical production functions is often limited (U.S. Environmental Protection Agency 2009). This limitation is most obvious when policymakers attempt to predict the consequences of things like lost wetland acreage, water diversions to urban use, intensive fish harvests, and nitrogen deposition to surface waters. We know that these things can reduce the production of ecosystem goods and services like water quality and quantity, abundant species, and so on. But it is much harder to predict the magnitude of these effects with accuracy. Our current ability to "manage" ecological systems is limited by those systems' complexity and our relative lack of empirical knowledge of their functions.

Overcoming this ignorance requires investment in evidence-based ecology that explicitly focuses on the relationship between observable stresses to ecological systems and outputs (goods and services) that are socially important. Like clinical medicine, ecology is developing ways to consistently relate stresses (e.g., impervious land cover) and interventions (e.g., stream bank restoration) to clear outcomes (e.g., water quality, fish abundance). However, evidence-based analysis of biophysical production functions is complicated by several factors. First, nature's complexity means that causal relationships can only be tested using rigorous, data-intensive empirical and scientific tools that are difficult and costly. Second, the non-uniformity of environmental systems means that a causal relationship in one location may not hold in other locations or the magnitude of the relationship may not be transferable. Third, empirical analysis of causality requires collaboration between different disciplines (ecology and hydrology, for example).

To complicate things further, biophysical production systems are inherently spatial. Broadly, ecosystem service management requires *spatial* production functions that describe the dependence of species on the configuration of lands needed for their reproduction, forage, and migration; surface and aquifer water volumes and quality on land cover configurations and land uses; flood and fire protection services on land cover configurations; soil quality on climate variables and land uses; and air quality on pollutant emissions, atmospheric processes, and natural sequestration.

The science of biophysical production is already under way. But our ability to manage natural systems toward particular ends remains limited because our understanding of nature as a production system remains so limited. Even without the added complication of climate change, this lack of knowledge argues for precautionary investments in the protection and restoration of ecological systems. It also argues for expanded development of diagnostic monitoring and interventions in order to preserve or restore systems that become degraded. Policies designed to preserve and enhance natural wealth in the face of climate change must be designed with our ignorance of biophysical production in mind.

The second, *economic* mission is to measure the value of those goods and services. The economic mission requires us to track the presence of and changes to ecological outputs and then describe the benefits or costs of those changes. As noted earlier, natural resources and ecological systems are economically and socially valuable. We know that productive soils, wetlands, species, clean air and clean, abundant water are the foundation of all subsequent economic and social welfare. However, uncertainties associated with the production and delivery of ecosystem goods and services are mirrored by uncertainties regarding the economic value of those goods and services.

What ecological goods and services are valuable, and how valuable are they? These questions have occupied economists for decades. Because environmental goods and services are often public rather than traded in markets, economists lack information on the prices paid for those goods and services. The lack of explicit prices for ecological goods and services does not mean they have no value, however. The challenge is to get people to reveal the values they place on goods and services that are un-priced.[4]

We can make several broad statements about the value of ecosystem goods and services: the scarcer an ecological feature, the greater its value; the scarcer are substitutes for an ecological feature, the greater its value; the more abundant are complements to an ecological feature, the greater its value; the larger the population benefiting from an ecological feature, the greater its value; and the larger the economic value protected or enhanced by the feature, the greater its value.

Difficulties, such as lack of market prices, lack of data infrastructure, and sensitivity of values to location, demography, and technological innovation, mean that it is often problematic to evaluate gains and losses in our natural wealth. Combined with the uncertainties of biophysical production, our ability to manage ecological wealth is crude at best. In economic terms, the policy problem is that both the supply of and demand for ecosystem goods and services are highly uncertain.

The possibility of climate change magnifies those uncertainties. We will need and want to manage this wealth in the face of climate change. But the best policies will not be ones that assume we can manage ecological wealth with precision. Instead, they will be policies that acknowledge and address ecological and economic uncertainties.

The Risk of Ecosystem Service Losses: Ecological Hedging Strategies

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[4] Broadly, there are two ways to value un-priced goods and services. First, we can get people to state their preferences by asking them questions designed to elicit value. Second, we can look to people's behavior and infer natural resource benefits from that behavior. Houses near beautiful scenery sell for more than houses without scenery, for example. When people spend time and money traveling to enjoy natural resources, they signal the value of those resources. These are called revealed preferences.

The supply of ecological goods and services is economically important, and supply is at risk because of climate change and other threats. The economically rational response is a hedging strategy that provides insurance against costly reductions in the supply of ecosystem goods and services.[5] While we may not be able to eliminate the risk of climate change (hence the need to adapt), we can make investments in ecological production to reduce the negative consequences of climate change for ecological wealth.

OPTION VALUE AND ECOLOGICAL PRECAUTION

An economic rationale referred to as "option value" is well-established for protecting natural resources even when the resource's current benefits are less than the benefits of developing, degrading, or not conserving the resource. The economic rationale hinges on uncertainty regarding the social costs of environmental damage and the "irreversibility" of ecological losses. Both of these features are present in adapting to climate change. The previous section described the uncertainties surrounding both the supply of and demand for future ecosystem goods and services. Irreversibility relates to the cost and difficulty of ecological restoration and the tendency of ecological systems to shift to new, often durable equilibria once a threshold of stress or damage has been met, a possibility that is particularly salient in the face of a changing climate. Our ability to restore ecological systems or reverse ecological damage is limited (Mitsch et al, 1998). The concept of ecological irreversibility is clearly recognized in environmental economics.[6]

When environmental damages and their economic consequences are uncertain and irreversible, there is a value to delaying the damage until the uncertainty can be resolved or reduced. This value is termed "option value" and takes two general forms. The first is a risk-aversion premium, where the option value is like an insurance premium designed to ensure adequate future supply of a resource (Weisbrod 1964; Cicchetti and Freeman 1971; Krutilla and Fisher 1975; Brookshire et al. 1983; Smith 1983; Walsh et al. 1984). The second form does not rely on risk aversion and reflects the value of information gained from a delayed ecological degradation, during which time uncertainty regarding the scale of implied environmental damage is reduced (Hanemann 1989; Fisher 2000b; Pindyck 2000).[7]

The idea of option value in environmental economics is analogous to the value of options contracts in financial markets (Dixit and Pindyck 1994). In financial markets, it is valuable to purchase an option to some future action, such as a capital investment or the purchase of an

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[5] Hedging is an imperfect form of insurance. Insurance often completely covers the cost of a loss. Because of the scale and uncertainties associated with potential ecological losses from climate change, it is more accurate to speak of hedges, which rarely cover all contingencies.

[6] For example, Pindyck (2000, at 234) states, "The damage to ecosystems from higher global temperatures (or from acidified lakes or the clear-cutting of forests) can be permanent;" Fisher (2000a, at 191) states, "Biological impacts can be very difficult to reverse over any time span that is meaningful for human societies."

[7] The second version assumes that damage uncertainty is reduced by delay.

asset at a given price. Importantly, options are not obligations. Rather, they give a decisionmaker the option to take one action over another in the future upon the resolution of current uncertainties. The concept of ecological precaution (or the precautionary principle) is closely related (Gollier et al. 2000). Consider the intuition that we should be cautious with our ecological systems because we do not know (1) how we are damaging them and (2) what the economic consequences of that damage will be. The precautionary principle emerges from the same mindset.

Natural systems will be stressed by climate change, some to the point of collapse. As damage in these systems accumulates, their ability to supply goods and services will be diminished. But we do not currently know with any precision the magnitude, timing, and location of these losses. The pace and nature of climate change itself is part of the uncertainty. Global economic development and the future stresses it will impose on ecological goods and services are another. Finally, it is unclear how biological systems will adapt to a changing climate. Given these uncertainties and our inability to quickly reverse ecological losses via human intervention, a significant option value is likely to be associated with ecological protection, restoration, and reductions in human-caused stressors. Both sources of option value apply: the insurance-related rationale that averts the risks of future ecological wealth losses, and the value-of-information rationale that purports the benefits of delaying ecologically damaging actions whose consequences we might better understand in the future.

The option-value argument for ecological protection, while intuitive, could be more fully developed to motivate public and private actors to maintain the supply of ecosystem goods and services and foster natural adaptation to climate change.

THE PRACTICAL IMPLICATIONS OF OPTION VALUE

If we are to act on the basis of option value, we need to estimate the ways in which ecological and economic uncertainties can be reduced in the future and how we can act on better future information. The magnitude of the option value associated with protection depends on these factors. The debate within our society about the need to take strong actions to protect ecological systems can be disaggregated into differences of opinion regarding:

- the reversibility of ecological damages,
- the range of possible ecological losses and their economic consequences,
- the ability of biophysical science to reduce damage uncertainty and predict ecological change, and
- the rapidity with which uncertainties can be reduced.

All four factors relate to the option value associated with ecological protection. In general, the larger and more irreversible potential ecological damages are—and the quicker and more successfully we expect the science of ecological prediction to develop—the higher the option value is. In these circumstances, the value of information associated with delayed degradation is highest.

Unfortunately, the empirical assessment of these four factors is difficult. It is nearly impossible today to calculate the option value associated with conservation. Note that this is another strong argument for a recommendation made in the previous section: the need for much greater investment in evidence-based ecology that explicitly focuses on the relationship between observable stresses to ecological systems and outputs (goods and services) that are socially important.

In the meantime, it is desirable to make *some* investments in protection, restoration, and management of ecological systems to hedge against the ecological and economic risks associated with systems likely to be altered and disturbed by climate change. Again, it is difficult to make a clear argument for the appropriate magnitude of such investments. However, several principles can and should be applied to the hedging strategy we put in place.

First, analysis of ecological resilience is the best way to identify the most desirable hedging strategies. The concept of resilience captures the notion that species and ecological systems are able to adapt to shocks, stressors, and threats, but that resilience is itself a depletable feature of a natural system.[8] As an example, certain species may be able to adapt to elevated temperatures by moving to locations with lower temperatures (e.g., higher latitudes or elevations) but only if there is suitable habitat within those ranges and a path through which the species can migrate. If agriculture or other development limits that habitat, the species' resilience is limited. This example highlights that resilience can be managed by protecting the natural landscape's ability to itself adapt and provide needed forage, reproduction, and migratory resources. The growing discipline of ecosystem-based management emphasizes the need to evaluate ecosystems' ability to rebound from disturbances (McLeod et al. 2005). From this discipline arise two types of ecological hedging: refuges and investments in restoration and management of natural systems and their services.

The ecosystems-based management literature emphasizes the protection of refuges designed to maintain ecological processes and functions. In practice, these refuges have several general features associated with contiguity and connectivity: a minimum size and connections or pathways to other resources needed to support migration, reproduction, and forage (Roberts et

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[8] Albers and Goldbach (2000) explicitly link the concepts of ecological resilience and irreversibility.

al. 2001; Green et al. 2007). Examples of the latter are migratory pathways to allow the free movement of terrestrial species over often very large distances.

Accordingly, ecologists have proposed protected area networks, or refuges, designed with climate resilience in mind (McLeod et al. 2009). These networks are a response to the ecological production uncertainties noted in the previous section. While they are clearly desirable for ecological reasons alone, they also preserve the economic value of that ecological production. As a result, protected-area networks are one of the principle hedging strategies available to preserve ecological wealth.

The other main types of ecological hedging are investments in restoration and management of natural systems and their services. Like protected-area designations, restoration of wetlands, riparian forest buffers, and native plant species can enhance resilience and help ecosystems adapt to climate change. Similarly, water management (e.g., diversion of flows to stock subsurface aquifers) and land management (e.g., selective harvests, cropping practices, removal of invasive species) are ways in which we can hedge against the loss of ecosystem goods and services.

A second key hedging principle is the idea of a portfolio of investments. Because of the numerous uncertainties associated with ecological change, it is desirable for society to invest in a "diversified" portfolio of natural resources and systems. Ecological diversification should take place along several key dimensions:

- Hedge against losses in ecosystem goods we directly consume, such as agricultural soils, water, and species we consume for food.
- Hedge against loss of ecological processes, functions, and inputs necessary to produce those consumed goods.
- Hedge against changes in demand for ecosystem goods by demographic changes (population, industrial activity) associated with climate change.

Consider a concrete example: if we wish to hedge against the loss of marine fish populations on which we are dependent for food, we should consider the following forms of diversification: protecting numerous different species whose adaptive responses to climate change are uncertain and protecting the food webs on which these species depend (which themselves will adapt unevenly to climate change).

POLICIES TO ACHIEVE A DIVERSIFIED PORTFOLIO OF ECOSYSTEM FUNCTIONS AND SERVICES

The biophysical and social sciences have begun to develop tools and analyses necessary to identify the key elements of a portfolio designed to hedge against the ecological and economic risks associated with both climate change and the growing stresses placed on natural systems by demography and economic activity. A goal of the sciences should be to identify ecological hedging strategies based on the best possible prediction of climate and other stresses. As argued, however, this is an enormous challenge that will take decades. It is beyond our current capabilities to accurately value or price particular land uses, protected areas, marine reserves, or resource management options to take into account the full social value of ecological resources, even without the uncertainties presented by climate change.

In the meantime, then, how should policies be designed to foster investments in ecosystem services adaptation? First, we should realize that current environmental policies—even those designed in the most sophisticated manner—have not been based on climate adaptation objectives. Going forward, environmental policies should be designed and targeted in close collaboration with natural scientists engaged in adaptive ecological management and strategy. This paper has identified several cases where the science is already under way. It should be further encouraged. Also, policy design should take into account the economic value of ecosystem goods and services whose patterns of production are likely to change in the future.

Consider the following policy instruments and ways in which they could facilitate ecological hedging strategies:

- Public lands management

  The current U.S. portfolio of protected lands is large and provides opportunities for the management of water flows, land use, and land cover to facilitate ecological adaptation. The Department of the Interior and other public trustees should experiment with management practices designed to increase the resilience of ecological systems.

- Public lands designation

  Current U.S. public land holdings are designed to serve many public purposes. However, land acquisitions, wilderness, and other protected designations have not been made with climate adaptation in mind. A portfolio approach to adaptation may include new investments in land acquisition and protection and new land use restrictions.

- Marine resource management and protection

  As in the previous two examples, the designation of new marine reserves and fishery management practices could facilitate the resilience and continued productivity of ocean resources.

- Payments for ecosystem services

  Payments for ecosystem services, from targeted farm conservation payments to schemes that transfer revenues from water users to up-watershed landholders, typically focus on delivery of a single service. Such schemes can deliver a range of other ecological benefits, including resilience and adaptation benefits. Calculation of, and payment for, these additional benefits will create opportunities for greater investment in ecological resilience.

- Greenhouse gas markets

  Many carbon sequestration practices generate a range of associated biophysical effects that influence the broader delivery of ecosystem services and resilience. For example, reforestation can provide numerous potential ancillary benefits beyond carbon sequestration, including support for species abundance, recreation and subsistence benefits, and water supply. Greenhouse gas markets and other payments could and should take these differential benefits into account.

- Natural resource damages

  In the United States, responsible parties are liable for natural resource damages under Superfund regulation and the Oil Pollution Act. These laws require injurers to compensate the public for the lost economic value associated with damaged natural resources. Federal agencies, including the National Oceanic and Atmospheric Administration and Department of the Interior are the designated trustees responsible for the assessment and adjudication of these damages. Natural resource damage practices should be adapted to capture the possibility that resource injuries are degrading resilience and option value.

Many other policies could be adapted to foster ecological resilience, including rules governing wetland loss mitigation, tax laws that affect the incentive to donate conservation easement on private property, local zoning regulations, designated water use determination under the Clean Water Act, and the definition of critical habitat under the Endangered Species and Magnuson-Stevens Acts.

Conclusion

Our economies, factories, and households depend on a wide range of "free" ecosystem goods and services that are often taken for granted. As the human footprint grows, however, ecological goods become scarcer. Climate change will impose new, additional stresses on natural systems that are likely to further degrade natural resources and accelerate their depletion and scarcity. Because ecosystem goods and services are often public goods—not owned, traded, or guarded by property rights—their management and protection is weak relative to conventional goods. We cannot look to markets to properly signal scarcity and generate the appropriate incentives to restore and invest in ecological wealth. Instead, we must rely on public policies and government action.

The policy challenge is significant given the complexity of natural systems and chronic under-investment in the measurement and science of natural wealth. Without clear market signals, we are uncertain about the demand for ecological services today and even more unsure about our demand in the future. A greater problem is that we are often unsure of how nature "produces" ecological wealth. Ecological change is rarely simple and related to only one or two factors. Instead, ecological production often occurs over large distances and long time scales and according to processes that we are only beginning to understand.

Though they describe the motivations with different language, economics and ecology agree on the need to manage for ecological resilience, be cautious when we stress systems in ways that can lead to irreversible change, and develop a portfolio approach to conservation, restoration, and management of natural systems to reduce the risks of ecological collapse. The economic view of *any* decision characterized by irreversible consequences and uncertainties that can be at least partially resolved through delay is that delay has an economic value. This does not necessarily imply that we should always delay an environmentally damaging housing development, fishery, dam, or power plant. It does mean, though, that we should invest in science and economics designed to better understand the "option value" of ecological protection.

In the meantime, it is economically rational to devise hedging strategies as best we can. For ecosystem goods and services climate adaptation policies should foster investments in geographically diverse *portfolios* of species, lands, resources, and ecological systems designed to hedge against future losses in supply or increases in demand brought about by climate change. Creating these portfolios will require coordinated analysis by natural and social scientists. A variety of existing policy mechanisms in the United States and abroad can put such portfolios in place. The policy mechanisms themselves do not present the real challenge. The real challenge is better understanding of ecological production and the role non-market ecosystem goods and services play in our economic well-being.

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