Linking ecosystems to landscapes

A challenge for ecologists

Dennis F. Whigham

This contribution is based on the assumption that solutions to most environmental problems will require the application of knowledge based on an understanding of how ecosystems and landscapes function and how they are linked in time and space. I also assume that almost all plans to solve environmental problems will be made with the knowledge that they are based on a limited and imperfect scientific understanding of how ecosystems and landscapes function. This dilemma creates problems for scientists who are often asked to provide commentaries on or solutions for environmental problems. Nowhere is this situation more obvious than in the fields of ecosystem and landscape ecology, where the information base is often limited and where experimental studies are often difficult to conduct because of problems of scale.

A challenge for ecosystem and landscape ecologists is to use their limited knowledge to demonstrate the ways in which ecosystems and landscapes are linked and use that information to develop tools that can be used to make informed and ecologically sound environmental decisions. It is a daunting challenge, but one that needs to be done if ecologists are to use their knowledge to benefit the societies in which they live and work. It is my belief that ecologists, particularly ecologists who are trained to understand patterns and processes at the ecosystem and landscape levels, have critical knowledge and insight that can be used to develop solutions to environmental problems, or better yet avoid or minimize them.

The objective of this contribution is to make three points. First, I will demonstrate that workable solutions to large-scale and economically important environmental problems require an ecosystem and landscape approach. Second, I will use examples to demonstrate that, as we come to know more about how ecosystems interact at landscape scales, we are likely to find seeking solutions to environmental problems that will require us to work over a wide range of scales and in ways that are at times not obvious. Finally, I use an example from the US to demonstrate how principles from the fields of ecosystem and landscape ecology can be used to develop tools to provide solutions to pressing environmental problems.

Using knowledge about ecosystems and landscapes to solve large-scale and economically important problems

In recent years, ecosystem and landscape ecologists have been effectively involved in developing solutions to economically

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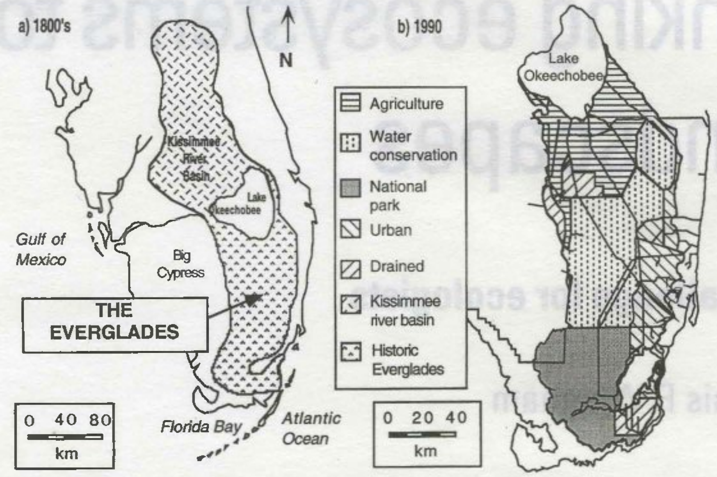


Figure 1• Map of south Florida showing how much the landscape has been changed since the 1800's as a result of human activities (left part of the diagram). The right part of the diagram demonstrates that much of the area that historically supplied water to the Everglades has been modified for purposes of agricultural production, water storage, and water diversion. Source: Gunderson *et al.* (1995)

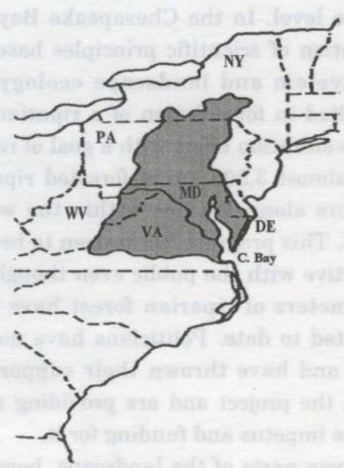
important environmental problems that involve large areas that encompass different types of ecosystems that interact in complex ways. Ecologists have become involved in these processes, in part, because the public, politicians, and bureaucrats have recognized that previous approaches to landscape management have often resulted in larger and more serious problems because decisions were made without any understanding of how ecosystems and landscapes function. Two examples serve to demonstrate this point.

The south Florida landscape includes terrestrial, wetland, and aquatic ecosystems that support a high level of biodiversity and provide numerous goods and services that are of economic value (Davis & Ogden, 1994). Everglades National Park is perhaps the best known part of the south Florida landscape (Figure 1). The common feature of south Florida ecosystems is that they are hydrologically linked and many, including Everglades National Park, are threatened by a long history of anthropogenic activities including water diversions, invasions of exotic species, and eutrophication, primarily associated with agricultural practices (Gunderson *et al.*, 1995). There is now a general understanding that there needs to be an extensive and expensive effort to restore the south Florida landscape to preserve its biodiversity and ecosystem integrity, including areas of special interest such as Everglades National Park (Harwell, 1997). There are no easy solutions to resolving the mistakes that were made in the past, and arguments about who has been or is responsible for the current problems have resulted in intensive political debates and the expenditure of millions of dollars in lawsuits. A general regional plan for restoration has been formulated through a series of discussions guided by individuals familiar with ecosystem and landscape ecology (Harwell, 1997). The elements of the approach that were used to develop restoration goals for regional ecological sustainability are shown in Table 1. The most important feature to note in Table 1 is that the final plan was based on an understanding of ecosystem and landscape principles. A similar, yet less formal, landscape and ecosystem approach has been used to guide efforts to restore the ecological health of the Chesapeake Bay.

The Chesapeake Bay (Figure 2) is the largest estuary in the US, having a catchment basin of more than 165,000 square kilometers in the states of Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia and the District of

Columbia. The catchment also includes the large urban and suburban areas of Baltimore, Washington, and Richmond. Many changes have occurred since Europeans first came to the region but the cumulative impacts of human activities have resulted in severe degradation of the Chesapeake Bay ecosystem including the demise of several fisheries resulting in significant economic decline. At the same time, however, the recreational value of the estuary has increased enormously as the regional population has grown. There are now several large and politically powerful organizations that have helped direct public opinion to the recognition that something needs to be done to restore the ecosystem and its resources. SAVE THE BAY is a common and widely recognized rallying call throughout the region.

Most of the environmental problems associated with the Chesapeake Bay have resulted from excess nutrients, toxic chemicals and sediments that have been discharged from point and non-point sources within the watershed. Still other problems have resulted from the direct loss of habitat and over-fishing. A large multifaceted effort called the Chesapeake Bay Program is now underway to remedy the results of many years of benign neglect. It is a large program that involves close and legal partnerships between the national government and the states. It also includes significant input from the scientific community as well as public and private environmental organizations. Partial success has occurred in some areas. Most of the problems associated with toxic chemicals have been solved through abatement programs at the sources. These efforts required little understanding of ecosystem and landscape functions beyond the fact that the discharges were harmful to the environment and humans. Most issues relative to over-fishing are now somewhat under control but there is still much to be done with regard to reductions in nutrients and sediment inputs to the Chesapeake Bay, especially from non-point sources of pollution. Ecosystem and landscape ecology research have shown that runoff from agricultural fields is the primary source of nutrients and sediment (Jordan *et al.*, 1997a, 1997b). Scientific research has also shown that it is important to have ecologically functional buffer strips of vegetation (also called riparian buffers) adjacent to streams (Peterjohn & Correll, 1984, Lowrance *et al.*, 1995, Weller *et al.*, 1998). Riparian buffers form a protective mantel around stream systems and provide connectivity and habitat at the land-



• Figure 2
Map of the Chesapeake Bay (C. Bay) and its watershed (shaded area). The Chesapeake Bay is the largest estuary in North America. It receives about half its water volume from the Atlantic Ocean and the remainder from a 64,000 square-mile (16,575,923 hectares) drainage basin or watershed that is shown as the shaded area. The watershed includes parts of the states of New York (NY), Pennsylvania (PA), West Virginia (WV), Delaware (DE), Maryland (MD) and Virginia (VA). More information on the Chesapeake Bay and its watershed is on the Chesapeake Bay Program Website: http://www.chesapeakebay.net/bayprogram

• Table 1
Steps used to develop a model that would off the mutual sustainability of agriculture systems and the Everglades within the south Florida ecosystem. The end result of the charette process was the development of a model that showed the distribution of elements of a restoration and management plan to sustain the ecological and economic integrity of the landscape. Modified from Harwell (1997).

Step 1:	Develop a conceptual model to characterize how human activities interact with Everglade ecosystems.
Step 2:	Develop a set of ecosystem management principles that would be needed to sustain Everglade ecosystems.
Step 3:	Define the geographic limits of regional ecosystems and identify ecosystems that need to be included in management plans.
Step 4:	Determine the range of ecological conditions that exist for each type of ecosystem in order to evaluate ecosystem health.
Step 5:	Characterize natural and anthropogenic stresses that occur in each type of ecosystem.
Step 6:	Characterize the social factors and mechanisms that influence Everglade ecosystems.
Step 7:	Characterize the legal, economic, institutional, and other social factors that affect the mechanisms that influence Everglade ecosystems.
Step 8:	Characterize human values and societal preferences relative to Everglade ecosystems.
Step 9:	Establish scenarios under which ecosystems would be sustainable based on ecological conditions and societal values and preferences.

scape level. In the Chesapeake Bay, application of scientific principles based on ecosystem and landscape ecology has resulted in formulation of a riparian forest restoration effort with a goal of restoring almost 3,500 km of forested riparian buffers along streams within the watershed. This program has proven to be very effective with the public even though few kilometers of riparian forest have been planted to date. Politicians have noticed this and have thrown their support behind the project and are providing much of the impetus and funding for it.

In some parts of the landscape, however, riparian buffers may not play an important role in removing nutrients and sediments in runoff from agricultural fields. This is especially true in areas where water primarily passes beneath the rooting zones of riparian vegetation as groundwater (Bohike & Denver, 1995). Riparian buffers may also not be as effective in agricultural landscapes which are flat and where water is removed from fields through networks of drainage ditches which convert runoff from a diffuse to a point source. In those situations, riparian buffers are not able to provide much water quality improvement because runoff moves through the buffer strip quickly with minimum contact. Ecosystem and landscape theory can, however, also be used in those situations to develop management plans for water quality improvement.

Restored wetlands rather than riparian buffers, for example, can be used to effectively remove nutrients and sediments from agricultural fields. We have found that restored wetlands located at the topographically lowest portions of agricultural fields can remove as much as 70% of the phosphorus and 60% of the nitrogen in runoff from agricultural runoff (Jordan *et al.*, in press). In addition to improving water quality, the restored wetlands also provide for increased biodiversity.

Issues of scale

Landscape ecology is still a relatively new field and practitioners work to develop a scientific underpinning for the discipline (e.g., Forman, 1995). Landscape scale is an issue that is often discussed and it is clearly important. The point that I would like to make is that societies will be challenged by environmental problems at all possible scales and it is unlikely that there will be any single paradigm that will be used to solve environmental problems in which scaling is important. Ecologists will have to work across a wide range of scales to provide solutions to the many problems that they will be asked to address. In some instances, existing ecological knowledge will be adequate to solve problems at small and large scales while in others it will be completely inadequate. In other instances, the scale presented by a particular environmental problem may not be known or understood and there may be little ecological knowledge to help provide answers and solutions. A few examples demonstrate these points.

First consider two biodiversity examples from The Netherlands where the operational scales are known, where the environmental problems have been recognized and where society and the government have expressed concern about continued degradation and loss of species diversity. In both examples, ecologists have applied scientific knowledge of ecosystems and landscapes to provide potential solutions which have resulted in active management.

Forests and grasslands that occur on calcareous well-buffered soils are ecosystem types that are widespread in Europe but of limited extent in The Netherlands. To reverse the trend of declining species diversity that resulted mostly from changes in land-use practices (de Kroon, 1986) and atmospheric nitrogen deposition (Bobbink *et al.*, 1998), effective management approaches have been developed to restore or maintain their historically characteristic biodiversity. There are still other problems associated with chalk grasslands but their distribution in The Netherlands is known, there is a lot of knowledge about how they function ecologically and management decisions have been made that are based on sound ecological principles such as by cutting and grazing of vegetation (Bobbink & Willems, 1993).

Managing species diversity in fen ecosystems is actively pursued in The Netherlands (Grootjans *et al.*, 1998). To maintain certain species associated with fens, restoration programs based on research and an understanding of landscape processes, especially patterns of succession, have been developed. While this activity is costly, it is absolutely essential if certain species are to be maintained in this highly managed agricultural landscape (Beltman *et al.*, 1995, Barendregt *et al.*, 1997).

The chalk grassland and fen examples from The Netherlands are examples of environmental problems for which management programs have been developed which have a high probability of being successful because they are based on existing ecological information. Not all environmental problems that have landscape components are as clearly defined as those two examples. In some instances, environmental problems may or may not be clearly recognized, mostly depending on ones viewpoint, or the landscape scale or scales that need to be addressed to find solutions to problems that are not well understood.

The current debate over the impacts of increasing carbon dioxide continues around the world, and particularly in the US where the debate is quite political. In addition, while most scientists agree that there is a problem, there is still a lot of debate in the scientific community about how different types of ecosystems will respond to elevated carbon dioxide, how the responses will be manifested around the globe, and whether or not vegetation responses will have a net positive or negative impact on global carbon dioxide levels (Wisniewski & Lugo, 1992). Much of the global change research is driven by global climate modeling, often with little ecological input, which are rather insensitive at the landscape scales at which we live and work.

Another major global problem is the movement of organisms around the world in ballast water moved from one continent to another by more and larger ships. The potential impacts of species invasions are enormous not only from the perspective of biodiversity but on local and regional economies. Not only is it possible for large organisms to move over great distances in ship ballast water but numerous planktonic organisms can survive long ocean voyages and they can bring other organisms with them such as parasites and viruses. Alien species such as the Zebra mussel can decimate native species and cause significant economic problems (Ram & McMahon, 1996). An effort is now underway to examine the potential impacts associated with the movement of ship ballast water but the magnitude of the problem is barely understood and management solutions are only beginning to be discussed (Ruiz *et al.*, 1998).

Not all problems are global in scale. Some problems are seemingly limited to small scales and may seem at first easy to solve but in the long run may prove to be quite difficult. Several species of terrestrial orchids in eastern North America are endangered due to human activities such as digging and habitat loss. A major limitation in dealing with biodiversity matters such as this is the lack of knowledge about certain aspects of the life history of the species. In the case of terrestrial orchids, the seeds are minute and very few studies have been made on the requirement that the seeds have for germination in nature (Rasmussen & Whigham, 1998a, 1998b). In addition, most terrestrial orchids appear to require mycorrhizas for seeds to germinate, for young plants to become established, and for older plants to survive and persist (Rasmussen, 1995).

To develop effective management strategies for terrestrial orchids, one must first understand the types of interactions that occur between the orchids and their fungi and develop techniques to make sure that both of them are present in the appropriate environment. What has been found, however, is that orchid-fungal interactions are much more complex and factors that influence the interactions may operate at several scales. Seeds of some species of terrestrial orchids, for example, only germinate and the seedlings only become established when they are associated with decomposing wood in the forest (Rasmussen & Whigham, 1998b). At this time, we don't know if the wood is the only habitat where the appropriate fungi will survive and grow or if decomposing wood contains chemicals required by both the orchids and the fungi. What is clear, is that we will have to consider the problem of orchid conservation at a larger scale and issues related to forest management will have to be considered.

The last example of scale is one where we don't know what scale is appropriate to consider as we seek to find solutions to an important environmental problem. *Pfiesteria piscicida* is a dinoflagellate that recently has been associated with fish lesions and fish kills in coastal areas of Maryland and North Carolina (Burkholder *et al.,* 1995, Steidenger *et al.,* 1996). *P. piscicida* has a complex life cycle with 24 reported forms, only a few which produce toxins. Most of the time *P. piscicida* lives a quiet and benign existence in the bottom sediments of estuarine environments but some factors, likely associated with the presence of secretions or excrement of schooling fish or high levels of nutrients, cause it to develop into the forms that produce toxins. The toxins cause fish to become lethargic, break down skin tissue, or kill them. Humans exposed to water that contains the toxic forms of *P. piscicida* may suffer memory loss, confusion, or gastro-intestinal problems.

P. piscicida outbreaks normally develop in the summer when temperatures are higher, when there are a many tourists in the coastal region, and when watermen are actively involved in commercial fish and shellfish activities. When there are outbreaks of *P. piscicida*, waterways are closed to all uses resulting in significant economic losses and social turmoil. Clearly we need to know more about what triggers this organism from being quite benign to highly dangerous and economically important. From the environmental side of the problem, we currently do now know what scale to begin to operate at to develop solutions because the areas where this species has caused problems receive runoff from not only local landscapes but from very large catchment basins. Solutions to this problem will indeed be ecologically challenging and politically interesting because they currently all involve heated debates associated with existing agricultural practices in the region.

With these examples, I have attempted to demonstrate that ecosystem and landscape ecologists need to be ready to work at a wide range of scales, that some problems will be easy to find solutions for while others will require a lot more effort - and very likely a lot more research.

Small scale habitat loss often results in large scale landscape effects

The final topic is an environmental problem that the ecological community in the US has not effectively been dealing with, the loss and conversion of what are described as dry-end wetlands. Dry-end wetlands occur in areas where flooding is intermittent or where the substrate may be saturated to the surface for a relatively short period of time. At the landscape scale, dry-end wetlands are most often associated with headwater streams of drainage systems or as isolated depressions. Examples of isolated depressional dry-end wetlands are vernal pools and playas in the arid west, temporary and seasonal prairie potholes in the mid-west, and seasonally flooded depressions and flats in the southeast (Mitsch & Gosselink, 1997). In other landscapes, dry-end wetlands are associated with stream systems where wetland conditions occur but where flooding is infrequent.

Most landscapes can be easily divided into watersheds (i.e., catchments). The watershed is a convenient landscape unit because most of the water that falls onto the watershed from the atmosphere exits it through a stream network. The first streams that water contacts as it flows from the uplands are called 1st order streams. When two 1st order stream come together they form a 2nd order stream. When two 2nd order stream come together they from a 3rd order stream, etc. The greatest linear extent of streams in watersheds is associated with 1st order streams and thus much of the total wetland area in a watershed is associated with small stream systems. Wetlands associated with small streams are infrequently flooded and the substrate may not be saturated for extended periods of time. Saturation of the soil, however, occurs often enough for the soil to develop characteristics of wetland soils and for wetland species to persist.

As indicated earlier, dry-end wetlands are also associated with other geomorphic landforms. The Prairie Pothole region (Figure 3) of the central US contains numerous isolated depressional wetlands of varying sizes (Van der Valk, 1989). The most numerous types of depressional wetlands in the Prairie Pothole region are temporary and seasonal wetlands which often contain little or no water during most of the growing season. Like dry-end wetlands associated with 1st order stream systems, temporary and seasonal Prairie Pothole wetlands have soils which are saturated long enough for wetland conditions to develop and for wetland plants to persist (Mitsch & Gosselink, 1995). During period of drought or years with below average precipitation, dry-end depressional wetlands are often planted with crops. Developers and farmers often ask for permits to alter dry-end wetlands, using the argument that the areas that they want to alter are small, often isolated from streams, and do not provide any valuable ecological functions either in the context of the individual wetland ecosystems, adjacent wetland ecosystems, or the landscapes adjacent to the wetlands. Most wetland ecologists intuitively know that these arguments are not correct and that dry-end wetlands are the first line of defense against nutrients and sediments that are discharged from heavily disturbed upland habitats. The arguments presented by those who would develop dry-end wetlands have been difficult to counter because of a lack of adequate ecological knowledge and because current regulations often allow small wetland areas to be permanently altered.

Ecologists need to change this situation by conducting research on dry-end wetlands and we need to clearly describe the important linkages that exist between them and adjacent uplands and down-

• **Figure 3**
Location of the Prairie Pothole region in North America. The majority of wetlands in the region are temporary or seasonal dry-end wetlands. Source: National Research Council (1995).

stream and nearby wetlands. But this is only part of what must be done because more and more wetlands will continue to be lost unless we can develop an effective assessment approach to characterize the ecological functions associated with wetlands, particularly dry-end wetlands.

A wetland assessment methodology that utilizes our existing level of ecological knowledge about wetland ecosystems and landscapes is currently being developed in the US (Brinson *et al.*, 1994, 1995). This system is called the hydrogeomorphic (HGM) approach to wetland assessment (Figure 4) and it is an interdisciplinary effort that is being developed as a tool which can be used by individuals with minimal ecological knowledge and training (Brinson *et al.*, in press). To describe the approach that we are using would require a lot more space than I have available in this article, thus I can only provide some of the basic elements. For further details, consult Brinson *et al.* (1995).

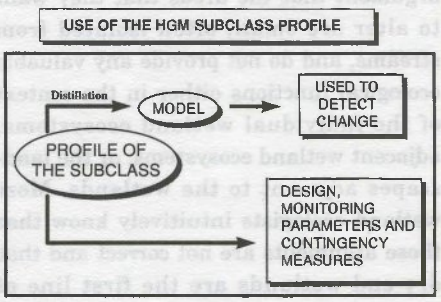


Figure 4 • Example demonstrating how information from reference wetlands can be used in the hydrogeomorphic (HGM) procedure for wetland functional assessment. The profile is developed from qualitative and quantitative information collected at reference wetlands. Information contained in the database gathered from reference wetlands can be used tot develop HGM models which are used to detect changes that might result from a proposed activity in a wetland. The information from reference wetlands that are used to develop the subclass profile can also be used to guide and evaluate mitigation activities.

First, it is important to note that the HGM approach is based on ecological processes, referred to as functions, and not values. Functions are the physical, chemical, and biological processes that occur without any human intervention and they are the processes responsible for maintaining ecosystems. Values are assigned by society, they may or not be related to ecological functions and they vary from one group of people to another. Water quality is one example. Ones view of water quality in a remote area of Norway is likely to be different than another persons view of water quality in The Netherlands. Thus, to be applicable over a wide range of wetland types, the HGM approach need to be based as much as possible only on ecological properties of ecosystems and landscapes.

The HGM approach is based on the assumption that most of the ecological processes that occur in a wetland are based on where the wetland occurs in the landscape, what the source of water is to the wetland, and how the water moves through the wetland. With knowledge of these three elements, we have been able to develop models that can be used to scale ecological functions and thus used to compare wetlands with each other (Brinson *et al.*, 1995). Perhaps the most important element of the HGM approach is that the models are based on data compiled from a set of wetlands that are chosen to represent the range of ecological conditions that are found for a type (e.g., class) of wetlands in a particular area. The wetlands that are included in this data set are called reference wetlands. It is the development of a reference data set that takes the most time but it is also most important because it can be used for a wide range of purposes

Models that are based on data from the reference wetlands are used to assess the impacts of proposed projects to assist with making decisions of whether or not the projects should be allowed and what will be required if they are permitted (Figure 4). If it is decided that a wetland related project will be approved but that it will be necessary to restore wetland functions to replace the ones that are lost during the project, the same reference wetland data set can be used to assess the ecological conditions at the site where the mitigation will occur. Information in wetland reference data sets can also be used to develop detailed plans to guide mitigation plans and the models can also used to evaluate the success or failure of a mitigation. What is equally important is that the reference sites represent locations which can be used for training individuals who use the models, no matter what the purpose.

We are still early in the process of development of this assessment system in the US but we believe that is offers the potential to bring some ecological reality into the arena of wetland assessment because it incorporates basic ecological knowledge of how ecosystems function in a landscape context. A European counterpart of the HGM method is being developed in the PROTOWET project funded by EU-DGXII, in which the Utrecht Landscape Ecology group is an active partner (Maltby *et al.*, 1996). It will be worthwhile to develop synergy between these initiatives which will help to develop appropriate tools for assisting with societal decisions on wetlands.

Summary

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D.F. Wigham
Landschap 16/1

The impacts of human activities occur at all scales and we are becoming increasingly aware that many environmental problems will only be solved or managed through the application of ecological principles, particularly principles related to ecosystems and landscapes. While ecosystem and landscape ecology are still emerging fields of study, enough information is known to provide guidance toward the solutions of some environmental problems. In other instances, however, solutions will be much more difficult because of a lack of basic biological and ecological knowledge, particularly knowledge about linkages across different scales of biological and ecological organization. I have used several examples to demonstrate that ecologists need to be prepared to work over a wide ranges of scales if they are to play key roles in solutions to environmental problems. While continued research will add to the existing knowledge base, ecologists need to understand that there will never be an adequate amount of information. Solutions to many contemporary environmental problems will be have to be developed through the application of existing knowledge about ecosystems and landscapes.

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