Ecosystems (2001) 4: 452–460
DOI: 10.1007/s10021-001-0106-0

ECOSYSTEMS

Managing Critical Transition Zones

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ABSTRACT

Ecosystems that function as critical transition zones (CTZs) among terrestrial, freshwater, and marine habitats are closely connected to the ecosystems adjacent to them and are characterized by a rapid flux of materials and organisms. CTZs play various roles, including mediating water flows, accumulating sediments and organic matter, processing nutrients, and providing opportunities for recreation. They are particularly difficult to manage because they tend to be small, albeit important, components of large watersheds, and managers may not have control over the entire landscape. Moreover, they are often the focus of intensive human activity. Consequently, CTZs are critically important zones, and their preservation and protection are likely to require unique collaboration among scientists, managers, and stakeholders. Scientists can learn a great deal from the study of these ecosystems, taking advantage of small size and the importance of fluxes, but a good understanding of adaptive management strategies is needed to establish a dialogue with managers and stakeholders on technical and management issues. An understanding of risk analysis is also important to help set meaningful goals and establish logical strategies that include all of the interested parties. Successful restoration of a CTZ is the best test of the quality of knowledge about its structure and function. Much has already been learned about coastal CTZs through restoration projects, and the large number of such projects involving riparian CTZs in particular suggests that there is considerable opportunity for fruitful collaborations between scientists and managers.

Key words: adaptive management; ecosystem restoration; landscape ecology; risk analysis; wetlands.

INTRODUCTION

Critical transition zones (CTZs) are hybrid ecosystems that serve as conduits for substantial fluxes of materials and energy from one adjacent, clearly defined ecosystem to another. They are considered hybrids because they are strongly influenced by the ecosystems that they link, even though they may also contain distinctive endemic plant and animal species. For example, intertidal mangrove forests and salt marshes are bounded on one side by the ocean, which washes them with tides, and on the other by terrestrial upland ecosystems, which deposit sediments through river flooding and overland flow (Levin and others 2001); thus, both terrestrial and marine animals use these wetlands. Riparian zones are CTZs that link aquatic ecosystems, whose waters flood them periodically, with terrestrial ecosystems, which generate nutrient- and sediment-laden runoff (Palmer and others 2000). Not all CTZs are wetlands. Water moves from one ecosystem to another through geologic formations such as karst formations and volcanic

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Received 25 February 2000; accepted 6 February 2001.

**Corresponding author; e-mail:* kewel@gte.net landscapes. A cliff is a CTZ that is a geologic formation from which water may seep. It is transitional between ecosystems at the top and bottom, and it may trap and funnel rainwater and fog, much like plant canopies. CTZs can be completely subterranean, such as deep soils under riparian zones and soils under adjacent uplands that regulate the flow of water into groundwater and riparian zones (Bardgett and others 2001). The hyporheic zone, where groundwater and surface waters meet, is an important subterranean CTZ that serves as a mechanical and biochemical filter, controlling rates of water flow, material flux, and biotic activity (Stanford and Ward 1988; Brunke and Gonser 1997; Boulton and others 1998). Because of these substantial interrelationships, management practices that affect a CTZ or any of its adjacent ecosystems must take the entire complex of ecosystems into account.

Most CTZs have distinctive structural characteristics that are shaped by the passage of water and the deposition of materials. Water movement through these ecosystems often causes rapid turnover of materials and sometimes of organisms, creating a unique environment that may appear highly variable in the short term but, if left in its natural state, demonstrates considerable stability over the longer term. When the flow of water is slowed, as by levee construction or water withdrawals, sediments and other materials settle out and accumulate. Wetland CTZs usually include distinctive zones generated by hydrologic flows. For example, tides and salinity control gradients in mangrove forests to a large degree (Ball 1998), whereas the flooding regime defines bands of vegetation diversity in riverine CTZs (for example, see Wharton and others 1982; Poff and others 1997). Sediment size and water velocity affect sediment deposition patterns, which may change dramatically over time. Cliffs and rock outcrops are also shaped by the erosive forces of water and often contain rich deposits at the base. They may contain remarkably stable communities (Kelly and Larson 1997). Caves and streams develop in limestone formations, and pockets of allochthonous organic matter provide habitat for a diversity of blind cave-dwelling invertebrates and fish (Culver and others 1999). The importance of water and material flows, along with the accumulation of allochthonous or eroded materials, is probably the only characteristic common to all CTZs. Some have low species richness relative to surrounding ecosystems, whereas others are speciose; some are especially attractive to migratory animals, while others provide habitat for endemic species.

Because of human population growth and urban and agricultural development, CTZs have not fared well. Many wetland CTZs were underrated in terms of ecological importance because they are often relatively small in surface area and can be quite narrow (if long); thus, they typically occupy only a small percentage of the total habitat in a given region. Many were devalued because they could not be cultivated easily or modified for shoreline development, or because they provided habitat for undesirable species (for example, biting insects). Therefore, they were often filled, dredged, or otherwise substantially altered. Some CTZs were discounted entirely because they were subterranean or otherwise inaccessible, and so were used by humans for belowground storage, such as wastewater disposal. Cliffs were commonly quarried. Even now, many CTZs remain threatened. Rock climbers disrupt ancient and fragile plant communities (Larson and others 1999). Pollutants from agricultural fields affect water quality in caves (Boyer and Pasquarell 1996; Tranter and others 1996) and in hyporheic zones and adjacent fresh waters (Lake and others 2000). Constructing dikes and roads without regard to downstream wetlands and riparian buffer zones results in adverse effects from changes in flow dynamics, sediment transport, and loss of habitat (González 1987; Naiman and Décamps 1997; Petrolera Ameriven 1998; Lake and others 2000).

Many CTZs provide valuable services to humans (Table 1). First, slowing the overland flow of water makes many of them important in flood mitigation. Second, the accumulation of sediment and organic matter not only protects downstream ecosystems, but the CTZ itself becomes a useful site for monitoring environmental impacts and occasionally, under special circumstances, for helping to preserve archaeological artifacts. Third, CTZs are often crucial sites for the storage, transformation, and uptake of nutrients that enter them naturally or as a result of agriculture and other land uses. The conversion of riparian forests to agricultural land along the Mississippi River and its tributaries, with the subsequent loss of nutrient storage and transformation functions, is believed to be a major cause of the formation of the hypoxic zone in bottom waters of the Gulf of Mexico, where low oxygen concentrations result from reduced mixing of the water column combined with high loads of decomposing organic matter due to agricultural runoff (Rabelais and others 1996; Malakoff 1998). Finally, many CTZs are magnets for recreation and other human activity because of the diversity of their plant and animal life and their geologic attractions. For example, caves and eroded cliffs attract increasing num-

Table 1. Important Ecosystem Services Provided by Major Categories of CTZs

	Ecosystem Services			
Critical Transition Zones	**Flood Mitigation**	**Sediment Trapping**	**Nutrient Storage, Transformation, and Uptake**	**Recreation**
Marine				
Coastal wetlands	X	X	X	X
Estuaries		X	X	X
Mudflats and seagrass beds	X	X	X	X
Freshwater				
Littoral zones	X	X	X	X
Riparian strips	X	X	X	X
Terrestrial				
Seepage zones			X	
Caves		X	X	X
Cliffs		X	X	X

bers of sightseers and explorers. Commercial and recreational fishing activities are often concentrated in aquatic ecosystems that are adjacent to marine and freshwater wetlands, where nursery habitat and a detritus food supply are important to many species.

Managing a CTZ therefore requires an understanding of all the ways in which it is important as well as the ways that land uses in adjacent ecosystems may affect it; it also requires an ability to communicate its importance to stakeholders and to monitor the human activities that threaten it. CTZs are particularly susceptible to damage because of the complexity of the landscape interactions on which they depend, their typically narrow and linear form, and their attractiveness to people. In this paper, we will show how scientists and managers can benefit from collaborative efforts to ensure that CTZs are recognized and valued as integral to the larger landscape. We suggest some ways that their structure and function can be preserved, or even restored, if need be. More complete syntheses of function and biodiversity in CTZs are given in Levin and others (2001) and Bardgett and others (2001) for marine and terrestrially linked systems, respectively, and will not be repeated here.

THE ROLES OF SCIENTISTS AND MANAGERS

Managers of ecological systems make and implement decisions on land-use practices. They are often the primary interface between a piece of land, such as a park or a nature reserve, and the people who want to use (or preserve) it. Most managers have sufficient background to be able to find and interpret scientific literature that can help them develop a management plan, but their primary responsibilities are usually to the stakeholders and their needs. Scientists who conduct research on landscape, ecosystem, community, and population processes help to create a theoretical and practical framework for monitoring and actively managing the land. Scientists can bridge the gap between the production of knowledge and the development of management strategies and monitoring plans by (a) recommending specific areas for reserves or other special uses, (b) conducting research on appropriate management practices (for example, species-specific practices for threatened and endangered species), (c) preparing environmental impact statements, (d) identifying scientific and geographic areas where critical data are needed, and (e) providing input on the design of restoration programs. There is a continuum of responsibility from scientist to manager, but the demands are so broad that few individuals can play all roles.

The pivotal role of CTZs in a landscape and the complexity of landscape interactions that drive them put these ecosystems at risk from a variety of sources. Critical inflows and outflows can be lost because of alterations in closely linked ecosystems. Substances such as pollutants and invasive species can be introduced inadvertently because of these same links; stakeholders can directly abuse CTZs through recreation, harvesting, or inappropriate management practices. These CTZ–landscape interactions and the prominent role that humans play

Table 2. Characteristics of Collaborative Management Methods Used in Management of Natural Resources and Agroecosystems

1. Many groups participate.
2. A new (perhaps virtual) institution is constructed to accommodate all the stakeholders.
3. The complexity embedded in the natural resource management issue under study is simplified to facilitate communication.
4. There is a direct relationship between the spatial scale of the natural resource and the number of stakeholders.
5. The collaborative effort usually focuses on a particular stage of the management process: information collection, planning, implementation, monitoring, or assessment.

Source: Blumenthal and Jannink 2000.

increase the need for scientists and managers to collaborate on research-based management.

The benefits of having scientists and managers work together are obvious, particularly if stakeholder needs are represented, but this kind of collaboration is still rare (Walters 1997). For example, insufficient communication from scientists to decision makers, along with the unwillingness of many scientists to play an active role in educating lay people about specific management issues, has been blamed for continuing wetland loss in Australia (Finlayson and Rea 1999). Several US federal agencies have made public requests for improved collaboration between managers and scientists. The National Estuarine Research Reserve System, within the National Oceanographic and Atmospheric Administration (NOAA), was established specifically to promote the role of science in conservation of marine CTZs (for example, see NOAA 1996). This program provides research grants for scientists and students to work in reserves, monitors environmental conditions, and encourages the practice of adaptive management with advice from scientific advisory panels established for each reserve. More recently, the National Park Service announced a plan to enhance the quality of science in the parks and to increase the role that science plays in management of park resources (Paul 1999), and the Fish and Wildlife Service called for scientists to help managers communicate with the public and promote a more complete understanding of ecosystem processes (Clark 1999).

To address the complexity of landscape interactions, as well as equally complex stakeholder involvement and expectations, a formal approach to risk analysis would be a useful way of bringing as much science as possible to bear on the management plans for CTZs. Risk analysis starts with characterization: defining the issues and formulating the problems while considering all of the stakeholders involved (Stern and Fineberg 1996). It includes a thorough analysis of a wide range of risks, with deliberation among all interested and involved parties. Some of these risks are best assessed by scientists, and others are best assessed by managers, but understanding and dealing with the full range require a real partnership among scientists, managers, and stakeholders.

Several approaches to risk analysis have been used to improve the management of natural resources and agroecosystems. Insights gleaned from these approaches indicate that high levels of interest and diversity are likely to be found among stakeholders, such that special organizational efforts may be required to accommodate them (Table 2) (Blumenthal and Jannink 2000). Studies have also shown that there is a positive relationship between the size of a natural resource and the number of stakeholders likely to be involved in a management effort. Because many CTZs are small but still of interest to a wide range of stakeholders, these ecosystems tend to attract inordinate levels of attention, making them particularly difficult to manage for their size.

One of the approaches most commonly used in natural resource management is adaptive management (*see* Walters 1986). This approach provides a questioning, hypothesis-posing framework for interpreting the results of monitoring environmental conditions and for deciding whether to continue or alter these practices. Scientists, who are more familiar with the technical and philosophical underpinnings of the tools needed for effective management, must take responsibility for communicating the essential elements of this understanding to managers; managers, with their critical positions as users of the tools, must understand the need for adaptive management and be willing to include scientists on their management teams. Stakeholders need to be included as well. The formal process of adaptive management often entails the use of computer models, because management decisions are often based on the prediction of ecological responses to interventions that are untried or have not been implemented in a comparable environment or stakeholder context. The only way to generate such predictions is to develop mathematical models of the system. This method may not always be practicable, but it can be very useful, as has been demonstrated by the research-based management of riparian and coastal ecosystems in particular (Walters 1997). Heuristic models for understanding how different management strategies might affect an ecosystem provide a means of educating both managers and stakeholders about indirect, nonintuitive effects (Carpenter and Gunderson 2001).

There is evidence that stakeholders can be receptive to the identification and protection of CTZs. The creation of a special management zone under a Sensitive Lands Ordinance in Park City, Utah, for instance, was undertaken to maintain the quality of life and long-term viability of the community (Bosselman and others 1999). It is striking that many of these "sensitive lands" were CTZs—for example, steep slopes, ridge lines, wetlands, and riparian zones. The ordinance was enacted in large part because local development was diminishing the aesthetic appeal of a community dependent on tourism. However, it was also designed to protect the wetlands and stream corridors because of recognition of their "important hydrologic, biological, ecological, and educational functions." At the same time, recognition of their importance is not sufficient in itself to ensure the protection of CTZs. For instance, although managers and decision makers at all levels of society around the world acknowledge the value of mangrove forests, particularly as a habitat for fish and commercially important invertebrates, managers have still not been able to convince stakeholders to leave them intact (Farnsworth and Ellison 1997). Certainly, in some cases, this problem is exacerbated by different stakeholders whose needs are in conflict with one another; people who fish may suffer loss of yield from the conversion of mangrove habitat to shrimp ponds, for instance (Naylor and others 1998).

Risk analysis involving CTZs will therefore require special efforts to explain such complex interrelationships to both the stakeholders and managers and to provide adequate opportunities for a wide variety of stakeholders to become involved (Table 2). Different groups of stakeholders should be encouraged to become involved at different stages of the management process, and conflict resolution and compromise are likely to be necessary to achieve a successful outcome.

Demonstration projects are useful as a point of communication between research scientists and managers, especially if good historical data and information are available for the site. These projects are mostly of local interest, but they can also be set up to include more general explanations, thereby increasing their societal value. Projects that include not only CTZs but adjacent ecosystems as well could be particularly enlightening.

One example is the large-scale voluntary mitigation effort that was recently undertaken by Public Service Electric and Gas (PSE&G) of New Jersey to restore natural ecosystem functions to a substantial area (more than 20,000 acres) of salt marsh and adjacent uplands that are associated with Delaware Bay, where the company operates a water-cooled nuclear power plant. At the core of the project was the restoration of almost 10,000 acres of diked salt hay farms and other degraded wetlands to a functioning CTZ (tidal marsh dominated by *Spartina alterniflora* that would enhance the exchange of production, especially of fish with the open estuary). However, other components involved the restoration of spawning runs for river herring, the provision of habitat for migratory birds, control of the invasive plant *Phragmites australis*, and the protection of local coastal communities. The planning and implementation of the complex project involved a cadre of scientists, managers, regulatory agencies, and private conservation organizations. Wetland ecologists were involved in developing success criteria and adaptive management plans (Weinstein and others 1997) that have proven practical in monitoring and maintaining predetermined goals and target trajectories. Details of this demonstration project can be found on the internet (http://www.pseg.com/environment/Estuary.html). The lack of available data on the natural functioning of tidal wetlands prompted PSE&G to sponsor the Marsh Ecology Research Program (MERP) as a seed project. The program currently is administered by the New Jersey Sea Grant Consortium, with supplemental funding from Sea Grant programs in several states. It continues to support innovative research to improve understanding of structure and function of coastal CTZs.

ACHIEVING A BETTER UNDERSTANDING OF CTZS

The ultimate test of the partnership between science and management is ecosystem restoration. All of the available information about the structure and function of an ecosystem must be distilled into a workable restoration design. The plan should have explicit goals and include practical contingencies that prescribe appropriate guiding actions in case the project deviates from the expected trajectory. The question of whether the restoration of structure leads to the restoration of function can best be addressed by collaborative teams of scientists and managers. Many more sites are now being restored than are being studied, and talented and interested managers can be a particularly valuable resource in this area. However, even though they often cost many millions of dollars for construction and monitoring, the majority of restoration projects do not involve scientists or incorporate experiments. Many of these projects are not adequately monitored, and many do not report on the nature and progress of the project; such a lack represents not only a waste of resources but the loss of an opportunity to gain valuable information as well.

Wetland restoration is a new but rapidly growing technique widely used for the mitigation of development, and early restoration sites have already demonstrated the usefulness of coordinating experimentation with management. From the recognition that the source of plants used for the revegetation of a salt marsh is important (McCray 2001) to an appreciation for the contributions of the substrate and invertebrate populations (Levin and others 1996), an understanding is slowly emerging that primary producers are likely to be the first to resemble the target conditions, followed by benthic infauna, but soil nutrient accumulations may lag by centuries (Craft and others 1999). Experiments with organic and inorganic additions (Langis and others 1991; Gibson and others 1994; Sardá and others 1996; Zedler 1996; Levin and others 1997; Boyer and Zedler 1998) have led to insights into ways in which the process of restoration might be directed or hastened, but it has also become clear that no consistent restoration trajectory can be followed and that some ecosystems may require more time than others to reach specific recovery targets (Zedler and Callaway 1999). It is now clear that the incorporation of natural substrate heterogeneity into restoration design may prevent restoration "failures," because different substrates support different vascular plant assemblages in CTZs.

The degradation of riparian zones has been of great concern because these CTZs are so important in regulating the movement of materials from land to water, providing nourishment for aquatic biota, acting as filters to reduce sediment and pollutant inputs to waterways, and damping floods (Gregory and others 1991; Naiman and Décamps 1997). There are several examples of successful partnerships that have been formed to restore these services. The Philadelphia Academy of Natural Science's Morris Arboretum has a "living exhibit" through which visitors to the arboretum and its learning center must pass. The entrance was once a neatly manicured grass lawn with a stream running through it. All vestiges of riparian habitat were long gone and in some areas replaced with concrete. In the last decade, resident scientists have worked with local groups of citizens and managers to create a model stream and riparian zone restoration project. Visitors driving up to the arboretum's entrance can now view a restoration project and then walk the grounds to see how stream banks were regraded and stabilized and vegetation was reestablished. Scientists are available to explain the pre- and postinstallation monitoring process. The process of adaptive management has been demonstrated with the Kissimmee River restoration project in Florida, in which iterative stages of manipulation and planning have already provided abundant information on the ability to restore both diversity and function of the floodplain (Toth and others 1998).

As a group, restoration projects represent an enormously valuable opportunity to study successional processes and to test relationships between structure and function on scales much larger (multiple acres/hectares) than is normally possible for the individual scientist. This possibility is particularly important given the difficulty in "scaling up" small-scale ecological experiments to the landscape level (Schneider and others 1997). Experiments incorporated into the initial design of a restoration site can provide important baseline information about structuring agents that may also be applied to healthy wetlands. Moreover, experiments of this sort can guide future restoration efforts and point to particularly critical conservation needs that can guide management decisions elsewhere. Thus, when managers must decide between strategies for CTZs that are under stress, they can refer to these restoration projects to help identify key species and processes that need management priority. Similarly, thoughtful comparisons of created and nearby natural systems can reveal differences that provide clues for ways to improve restoration (Moy and Levin 1991; Sacco and others 1994; Levin and others 1996; Scatolini and Zedler 1996; Talley and Levin 1999).

Managers have relied heavily on basic science for making such decisions as the appropriate widths for riparian buffer zones. Millions of dollars are being spent to re-engineer stream channels and replant vegetation (Manci 1989), but in most of these projects little or no effort has been devoted to pre- or postrestoration monitoring. Even when monitoring is included in a mitigation plan, noncompliance is common (Race and Fonseca 1996). Unquestionably, much more can be done. Scientists can collaborate with managers to design well-replicated sampling efforts, with control and/or reference site comparisons, to answer basic questions about both the structure (for example, water quality, biodiversity) and function (for example, denitrification rates, water flux) of newly created or restored riparian zones (Chapman and Underwood 2000). Indeed, this represents a unique opportunity for scientists. Many riparian or freshwater wetland restoration projects are mandated by law as mitigation measures, and the construction (channel reengineering and vegetation replanting) will be done regardless of whether research scientists are involved. Scientists increasingly view restoration projects as large experiments that provide an opportunity to study basic ecological processes, such as the factors that govern the assembly and maintenance of ecological communities (Palmer and others 1997). One such project is exploring the concept of depending on natural forces to control the revegetation of a riparian restoration site in Ohio (Mitsch and others 1998). Convergence in species complements in planted and unplanted wetlands suggests that self-design in a hydrologically open wetland may be sufficient, saving considerable time and resources. Scientists have the rare prospect of participating in whole-ecosystem experiments that may significantly advance basic ecological research, and managers gain an enhanced monitoring design that can contribute to effective adaptive management. The small size of many CTZs may actually be an advantage in this respect because a restoration project can be conducted at a workable scale.

The practice of ecosystem creation, whereby an ecosystem is designed explicitly to perform a particular service, such as wetland creation for wastewater treatment, extends the restoration concept. In constructed wetlands, dissolved nutrient concentrations are reduced as slow-flowing water passes through vegetation growing in low-permeability soil. An understanding of nutrient uptake in natural wetlands can serve environmental engineers as a tool that allows them to install and manage a natural system at much less expense than traditional wastewater treatment plants (Ewel 1997). While the manager takes responsibility for ensuring that the ecosystem performs its service, the scientist should assist in overseeing the effects of this new ecosystem on new and existing CTZs throughout the entire landscape. For example, if wetlands are created for wastewater treatment, the effects of the project on regional bird populations may need to be determined, but the additional effort of censusing birds is likely to be beyond the scope of a manager's expertise, budget, authority, or responsibility. Unfortunately, newly created ecosystems do not always function within the desired boundaries. Ecosystem managers who introduced mangroves into Hawaii in the 1920s to prevent sediments caused by erosion from newly exposed agricultural and urban lands from reaching offshore reefs did not foresee the effects these de novo CTZs would have on drainage and habitat for native and invasive wildlife species (Allen 1998).

To acquire a body of ecological knowledge that is sound enough to both restore and create ecosystems, clear goals must be set, rigorous monitoring must be done, and the results must be analyzed and reported appropriately (Hobbs and Norton 1996; Chapman and Underwood 2000). Unfortunately, in many cases, these clear requirements are not met (see Kondolf and Micheli 1995; Smokorowski and others 1998; Lockwood and Pimm 1999). Once the gap between scientist and manager has been bridged, an understanding by the general public of the scientific process and adaptive management is more likely to follow. The incorporation of mechanisms for citizen involvement in the monitoring and interpretation of results can then help to cement the alliance between managers and scientists (Cooperrider 1996).

CONCLUSIONS

Humans dominate much of the Earth's environment, yet we depend on the functioning of natural ecosystems for many important services, including the provision of food, clean water and air, and recreation. Consequently, partnerships between management and science must be forged to link emerging paradigms about how these ecosystems function with strategies that will ensure the continued provision of the vital system benefits on which we depend. The fact that some ecosystems are CTZs that link adjacent ecosystems mandates an understanding of how whole landscapes—even those as large as watersheds—function, rather than restricting the conservation or restoration focus to individual ecosystems. Small CTZs where human activity is particularly intensive need urgent attention. Partnerships between managers and scientists are necessary for designating effective reserves, determining appropriate management practices, improving our understanding of how ecosystems function, restoring degraded ecosystems, and even creating new ones. Scientists must work not only to increase our understanding of how CTZs function, but also to communicate that information to stakeholders and to find ways of incorporating that knowledge into a framework that can be used by managers. Scientists must temper their demands and recommendations to accommodate the needs of managers, they must be willing to take risks, and they must consider in advance the likely political fallout of a given decision. Managers, for their part, need to embrace adaptive management strategies and remain open to suggestions from scientists, even if that means accepting a certain level of short-term political risk to achieve the long-term goal of maintaining ecosystem integrity and health. Only when we have implemented these changes and increased the level of collaboration between scientists and managers, and when the stakeholders become actively involved in planning strategies, can we ensure that CTZs will continue to perform their essential functions within the landscape matrix.

ACKNOWLEDGMENTS

We thank Gina Adams and Janna Six (Colorado State University, Fort Collins, Colorado, USA), and Lijbert Brussaard (Wageningen Agricultural University, The Netherlands) for assisting with the organization of the SCOPE workshop "to assess the role of biodiversity of soil, freshwater sediments, marine sediments, and groundwater in the functioning of critical transition zones (CTZs)." Workshop support was provided by The Netherlands Ministry of Public Housing, Physical Planning, and the Environment; the Ministry of Agriculture, Nature Conservation, and Fisheries of the Netherlands; and an anonymous US donor. The participation of R. Kneib in this effort was supported in part by NSF award DEB 9629621 and EPA/NCERQA award R825147-01-0. L. Levin's contributions were supported in part by the NOAA National Seagrant College Program (NA66RG0477-R/CZ 140 and NA66RG0477-R/CA 150) and MERP Grant G99-15. M. Palmer's contributions were supported by NSF awards DEB 9622288 and DEB 9981376. P. Snelgrove was supported by an NSERC Industrial Research Chair.

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