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Integrating Soil Ecological Knowledge into Restoration Management

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Abstract

The variability in the type of ecosystem degradation and the specificity of restoration goals can challenge restorationists' ability to generalize about approaches that lead to restoration success. The discipline of soil ecology, which emphasizes both soil organisms and ecosystem processes, has generated a body of knowledge that can be generally useful in improving the outcomes of restoration despite this variability. Here, we propose that the usefulness of this soil ecological knowledge (SEK) for restoration is best considered in the context of the severity of the original perturbation, the goals of the project, and the resilience of the ecosystem to disturbance. A straightforward manipulation of single physical, chemical, or biological components of the soil system can be useful in the restoration of a site, especially when the restoration goal is loosely defined in terms of the species and processes that management seeks to achieve. These single-factor manipulations may in fact produce cascading effects on several ecosystem attributes and can result in unintended recovery trajectories. When complex outcomes are desired, intentional and holistic integration of all aspects of the soil knowledge is necessary. We provide a short roster of examples to illustrate that SEK benefits management and restoration of ecosystems and suggest areas for future research.

Key words: ecosystem processes, feedbacks, soil ecology.

Introduction

Restoration ecologists have long recognized the integral role of soil, particularly in its physical and chemical aspects, in the successful revegetation of degraded sites (Jordan et al. 1987). However, explicit incorporation of soil *ecological* knowledge (SEK), which acknowledges interactions among the principal components of the soil system as well as feedback between the aboveground and belowground ecosystem processes, into restoration remains in a relatively early stage of development (Aronson et al. 1993; Harris et al. 2006; Wardle & Peltzer 2007). Despite earlier attempts to demonstrate the importance of a soil's perspective for restoration efforts, a recent and useful review of research on restoration ecology makes only scattered references to soil processes and biota (Falk et al. 2006). Published restoration science in the primary literature commonly includes soil information associated with pre-restoration site assessment and the evaluation of specific soil amendments (Callaham et al. 2008). Recovery of nutrient capital or biogeochemical processes also motivates restoration activities, but examples where integrated SEK has been employed are uncommon.

In this article, we discuss restoration practice and research that is informed by SEK. The term "soil ecological knowledge" is used to indicate perspectives from the discipline of soil ecology that integrate soil physical, chemical, and biological factors and processes in context of plant–soil feedback. In particular, it is knowledge from soil ecology that can be used explicitly to inform restoration practice. A restoration approach that employs more sophisticated SEK differs from simpler approaches that consider soil factors in isolation or that separates aboveground from belowground ecosystem processes. We discuss a classification of restoration approaches arrayed along a gradient of increasing need for knowledge of soil ecology to attain the ecosystem structure and function of a particular reference condition. Additionally, we identify promising new research areas, where restoration projects may advance our understanding of soil ecology and where, reciprocally, a deepened knowledge of the soil system may enhance restoration practice.

The discipline of soil ecology has deep roots in soil science and organismal biology. Soil ecologists have merged

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these traditional disciplines to understand ecosystem processes, which have provided tools for elucidating concepts central to ecology as a whole (Coleman et al. 2004; Lavelle & Spain 2001; Bardgett 2005). For example, relationships between biodiversity and ecosystem functioning have been tested using model soil ecosystems (Lavelle 1996; Bengtsson 1998; Lawton et al. 1998; Setala et al. 1998; Behan-Pelletier & Newton 1999; Heneghan et al. 1999; Zak et al. 2003; Fitter et al. 2005). Furthermore, perspectives in soil ecology that focus on the reciprocal feedback of above- and belowground biota and processes have become increasingly central to ecology (e.g., Casper & Jackson 1997; Klironomos 2002; Setala 2002; Wardle 2002; Bardgett & Wardle 2003; Van Der Putten 2003; Wardle et al. 2004). The holistic perspective that integrates organismic and ecosystem processes at the core of soil ecology has provided explanations for patterns in the distribution, abundance, and composition of species, a fundamental organizing tenet in ecology (Tilman 1982; Bever 1994; Bever et al. 1997; Baer et al. 2005).

Soil biota is directly involved in key ecosystem processes (e.g., decomposition and nutrient cycling), and understanding such interactions has provided one of the unifying themes of soil ecological research over the past few decades (Swift et al. 1979; Wardle 2002). Because of the demonstrated key role in the regulation of ecosystem processes, application of insights from soil ecology has been useful in situations where desired outcomes go beyond simple enhancement of single factors such as productivity. For instance, soil ecology has made a substantial contribution to alternative agricultural practices, such as no-till cropping systems, by integrating conservation of physical, chemical, and biological properties of soil (Coleman et al. 2002). In this case, soil ecologists have demonstrated the importance of shifts from bacterial to fungal channels in soil food webs for the development of soil structure, soil organic matter (SOM) sequestration, and modulation of soil nutrient availability (Hendrix et al. 1986; Beare et al. 1995). Lessons gained from agroecology have inspired recent investigations of changes in microbial community structure following cessation of tillage and restoration of native vegetation (Allison et al. 2005; McKinley et al. 2005).

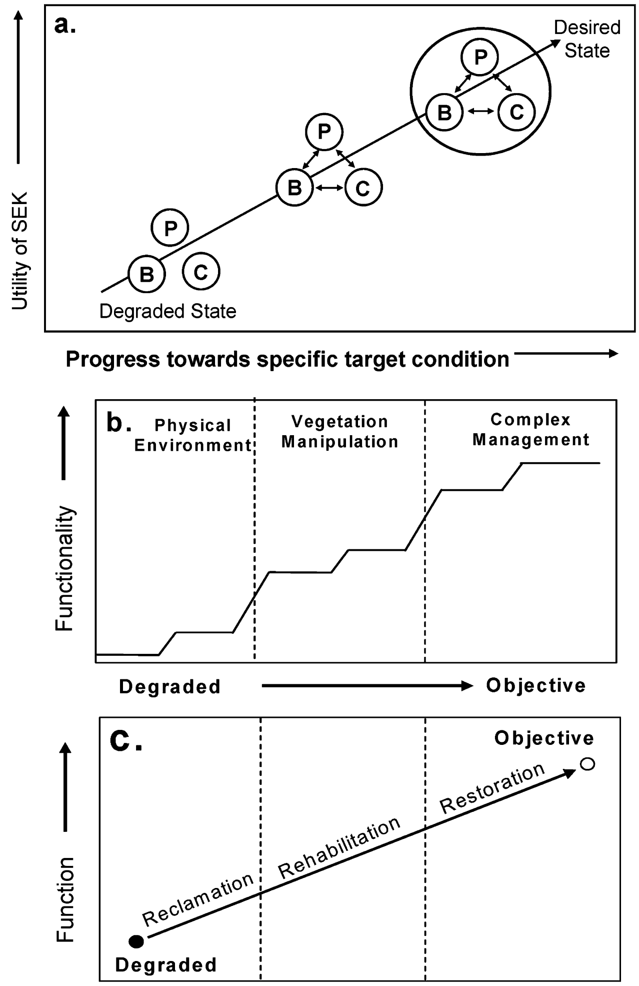

Figure 1. Framework for linking (a) SEK to existing theoretical models of ecosystem restoration (b and c). (a) When sites are heavily degraded, improved soil function may be achieved by simple single-factor manipulations of a given chemical (C), physical (P), or biological (B) attribute. For greater progress toward a target condition, an increase in the degree of complex SEK is required (and the consideration of interactions between P, C, and B components will be critical). (b) Physical and biological thresholds which must be overcome if restoration is to be successful (modified from Whisenant 1999). (c) The integral relationship between structural and functional attributes in ecosystem restoration (modified from Bradshaw 1987). See text for examples and further illustration.

Contribution of Soil Ecology to Restoration—A Classification

We propose that the relationship between SEK and restoration may be best considered in the context of the severity of the original perturbation, the goals of the project, and the resilience of the original ecosystem to disturbance (Fig. 1). Our conceptual model builds on previous models of ecosystem restoration (Bradshaw 1987; Whisenant 1999; Hobbs & Harris 2001). We surmise that the utility of SEK for achieving a restoration goal depends on the degree to which the restoration intent aims to achieve characteristics of a specified reference condition. Significantly degraded sites generally require active consideration of the soil, e.g., remediating oil spills (Kuyukina et al. 2003). Site remediation in circumstances where restoring pre-disturbance above- and belowground structure and function is not a priority and may require a manipulation of a single physical, chemical, or biological part of the soil system to improve a system's state relative to the perturbed state. For example, when a system has been so severely perturbed that plants simply will not grow (e.g., on soils contaminated by heavy metals, oil spills, brine scars), the restoration goal may be limited to reclaiming a specific structure or process to enable revegetation. This may be achieved through ripping, tilling, or contouring compacted substrates to improve aeration, infiltration, and root growth purposes (Ashby 1997; Jacinthe & Lal 2007); removing toxic chemicals; or altering pH (e.g., mine land reclamation). In some cases, this can involve as little effort as essentially "waiting" for extant microbial populations to act on the offending toxins. Some soil factors are known to be important in mediating the availability of toxins to the microbes (e.g., soil porosity, sorption/desorption of toxins to organic matter, pH, redox potential), and these factors are often targets for remediation (e.g., Mitsch & Jorgensen 2003). Such approaches are shown in the lower left-hand part of Figure 1a: the desired outcome is a relatively general one (getting some regrowth of vegetation), and the restorationist may manipulate soil factors without requiring a great deal of knowledge about interactions within the soil.

Restoration in the sense of returning an ecosystem to a specified reference condition, e.g., a historical state, both in terms of a specific community structure and ecosystem function, will require an increasingly sophisticated understanding of the soil and all its physical, chemical, and biological properties to achieve the desired goal. If a system is severely degraded, where soil food webs and processes have been highly altered, an integrated consideration of physical, chemical, and biological properties of soil and interactions between plants and soil will be required to restore all components of the perturbed ecosystem to a reference condition. This requirement for integrated SEK to achieve a specific desired system outcome is illustrated in the upper right-hand side of Figure 1a.

Finally, when the disturbance of a site is not so great as to overwhelm the resilience of a system (i.e., does not shift it beyond the self-organized processes and structures of the system [Gunderson 2000]), the need for management intervention may be minimal. However, when the disturbance is such that the system is degraded to a relatively stable alternative stable state, the need for SEK will be considerable.

Our model is summarized with a simple illustration (Fig. 1) in which an increasingly conscious integration of physical, chemical, and biological factors is required as the goal of approaching a specific desired ecological state is reached. Management options exist along a gradient from single-factor manipulations of physical, chemical, or biological elements (shown in Fig. 1a as P, C, and B in separate circles) to ones where a deliberate regard for a cascade of interrelated effects of manipulations of soil factors (maximum SEK) is required to bring about a particular outcome (shown as P, C, and B linked by arrows and bound together in a circle). We suggest that there are intermediate circumstances where a restoration outcome will require some knowledge of the interaction of effects (shown as P, C, and B linked by arrows).

Integration of Soil Knowledge: Case Studies

Hobbs and Harris (2001) and Hobbs and Norton (2004) suggest that abiotic and biotic constraints may stall the restorative process until thresholds are breached through human intervention (Fig. 1b; Whisenant 1999; see Fig. 1). The notion is that more degraded environments will require repairing the physical template (e.g., abiotic components) prior to restoring species composition (e.g., biotic components) and subsequently, the ecological functions representative of the reference system. Manipulations directed at relieving abiotic filters can be physical (e.g., reducing soil compaction), chemical (e.g., liming to alleviate acidity), or biological (e.g., using plants to stabilize and remediate toxic chemical conditions [Shimp et al. 1993; Qadir et al. 2002]).

We suggest that management aimed at fully restoring the ecosystem structure and function of a reference condition must integrate the physical, chemical, and biological factors of that system. We recognize that the soil is a proverbial "black box" where impacts of a given treatment are often evaluated by specific net outcomes despite the enormous complexity of interactions that may mediate the response and therefore determine those outcomes. For instance, manipulating a physical factor to alleviate compaction and promote greater plant production will likely simultaneously alter a suite of aspects of the soil system, such as soil carbon storage (Jacinthe & Lal 2007). The use of thinning, burning, and thinning plus burning as treatment variables in Ponderosa pine increased total inorganic nitrogen availability in forest restoration treatments compared with untreated controls (Kaye & Hart 1998) and resulted in higher understory diversity (Gundale et al. 2006). That is, the manipulation of the aboveground vegetation has well-characterized impacts on the cycling and storage of carbon and nutrient in the soil, and these cascades may be incorporated intentionally into management. Deliberate manipulation of soil that integrates holistic knowledge of the soil system will be more likely to achieve the restoration of several system functions or several aspects of community structure. For the purposes of illustrating the relative role of SEK in these examples, we consider both bioremediation and reclamation as types of ecological restoration. These will be considered alongside practices such as the manipulation of successional processes, which are used to restore community composition and function to a particular reference condition. The examples below illustrate a range of potential manipulations of physical, chemical, and biological factors available to the restoration. In many cases, single manipulations targeted at a physical, chemical, or biological component of the soil are employed; in most cases, these manipulations have consequences for other soil components though these are not always fully understood.

Physical Manipulations

Soil physical structure influences vegetation growth (Passioura 1991). When soil structure is degraded, the impacts, often mediated by a variety of other related soil physical characteristics (including those that relate water availability), can affect both plant growth and community composition (Burke et al. 1998; Kozlowski 1999). Physical manipulations to improve soil structure in highly degraded sites include a variety of tillage practices (e.g., disking, ripping, subsoiling; Scullion & Mohammed 1991; Ashby 1997), incorporation of polyacrylamide beads (Vacher et al. 2003), and topdressing (e.g., with nitrogenous fertilizers or with manure) (Ducsay & Lozek 2004; Johnson et al. 2006) (Callaham et al. 2008). Management of the physical soil substrate depth influences the overall quantity of water and nutrients available to support plant growth (Binkley et al. 1995; Andrews et al. 1998; Bowen et al. 2005). However, these often-effective practices can be expensive and time consuming, making them impractical for many restoration projects.

Manipulation of Soil Chemistry/Fertility

Fertilizers and chemical amendments are commonly used to improve restoration success (Lu et al. 1997; Jim 2001; Marrs 2002; Xia 2004). For instance, application of a phosphorus P fertilizer, N fertilizer, and lime, along with appropriate pasture seed mix was needed to effectively reestablish pasture in a New Zealand opencast coal mine reclamation (Longhurst et al. 1999). Restoration of former agricultural land, with residually high levels of inorganic nitrogen from long-term fertilization, may require manipulations to reduce soil fertility that favor the desired plant species adapted to nitrogen-limited systems (Wilson & Gerry 1995; Paschke et al. 2000; Suding et al. 2004).

Manipulation of soil chemistry and nutrition as part of ecosystem restoration is common, but consideration of the consequences of these practices on physical and biological soil properties is rare (Callaham et al. 2008). For instance, the stated goal of treatments where topsoil or "topsoil substitute" is added is to improve soil nutrient content and facilitate recovery of plant biomass and community diversity (e.g., Torbert et al. 1990; Clewell 1999). However, these amendments also introduce plant seed, mycorrhizal symbionts, and soil microbes and alter soil microenvironment and water relations by changing soil texture, depth, density, and porosity. As such, these "secondary" mechanisms may have significant influences on plant performance, the outcome of restoration activities. We suggest that identification of these soil ecological mechanisms and interactions will substantially contribute to understanding of the controls on restoration success.

Manipulation of Soil Organisms

Soil biota, both directly and indirectly, influence soil nutrient dynamics (Verhoef & Brussaard 1990; Lussenhop 1992; Brussaard et al. 1997) and can also influence plant community development and diversity (De Deyn et al. 2004; Kardol et al. 2005). Soil biota include microflora (i.e., bacteria and fungi), a wide range of functionally distinct nematodes and microarthropods, as well as a variety of macroinvertebrates (i.e., earthworms, beetle larvae, cicadas). Numerous studies have examined the effects of disturbance on soil microflora and fauna (e.g., Wardle et al. 1995; Brussaard et al. 1997), and soil biota are commonly employed as indicators of restoration success (Andersen & Sparling 1997; Todd et al. 2006; Callaham et al. 2008). However, soil fauna have rarely been directly manipulated to improve restoration success. One example of such manipulation is that of introducing earthworms to improve soil porosity and aggregate structure but with varying success (Butt 1999). Numerous studies have, however, directly manipulated mycorrhizae, either through additions of spores, inoculation of plants, or addition of soil inocula from undisturbed communities. The use of mycorrhizal fungi in restoration has attracted considerable attention in recent years, and increasingly sophisticated knowledge of the biology and ecology of this group of soil organisms can influence restoration.

The community and ecosystem consequences of mycorrhizal infection vary with mycorrhizal dependency of the dominant and rare species in a community (Bever et al. 2001, 2002). For example, if dominant species depend on mycorrhizae, then their presence may be necessary for restoring ecosystem function (Richter & Stutz 2002). Restoration of rare species that are mycorrhizae dependent may require inoculation for establishment and achieving the desired community composition (van der Heijden et al. 1998). Likewise, inoculation may be necessary to reclaim extremely degraded sites and maximize productivity of a limited species pool under such circumstances (Frost et al. 2001). Incorporating mycorrhizae in restoration requires an understanding of cascading ecological consequences from the relationship between belowground organisms, aboveground individuals, community structure, and ecosystem processes.

Restoring mycorrhizae to degraded soils is difficult (Cardoso & Kuyper 2006), and there is growing interest in using commercial mycorrhizae inoculums to improve restoration success, which prompts a number of research questions. Are commercial fungi as effective and as viable as native fungi (Caravaca et al. 2003; Querejeta et al. 2006; Tarbell & Koske 2007)? What are the risks associated with using non-native fungi in restoration? Under what circumstance will they benefit invasive plants more than native plants (Schwartz et al. 2006)?

Applying mycorrhizae requires knowledge about site conditions. Mycorrhizal fungi, for instance, may not grow at sites contaminated with heavy metals or where nutrients are very low (Vosátka et al. 1999). Additionally, they may also be inhibited by high levels of nutrients such as nitrogen from vehicles and fertilizers (Egerton-Warburton et al. 2007). Although plants exhibit less dependence on mycorrhizae with increasing nutrient (P) availability in soil, an unpredictable benefit from sustained populations is increased infection and plant survivorship during drought (Gemma et al. 2002; Allen et al. 2003; Walker et al. 2004; Querejeta et al. 2006).

The use of mycorrhizae illustrates an important part of the SEK model: in order to effectively incorporate mycorrhizae into a restoration strategy, a moderate level of knowledge about the interactions between the physical, chemical, and biological factors that prevail at a site is needed to drive the system along a trajectory leading to a specific outcome.

Integrated Manipulation

In most of the examples presented above, the manipulation of one component of the soil has implications for other components. Manipulations based upon an understanding of such cascading effects can therefore be performed intentionally to achieve a particular restoration result. In our model (Fig. 1), we propose that as the complexity and specificity of desired outcomes increase, intentionally integrated strategies become essential. Although many of the earliest restoration projects aimed at establishing vegetation of any sort, outcomes which specify complex species assemblages are now more prevalent (Bradshaw 2004). As the restoration process approaches desired functional and compositional attributes, we contend that a more nuanced understanding of SEK will be required.

Integrated Manipulation of Soil physical, Chemical, and Biological Properties: An Example Applying SEK to Combat Invasion

To illustrate what integrated strategies (applying SEK) may resemble, we discuss efforts to produce resilient restoration outcomes in the face of sustained invasion by exotic species.

SEK has been increasingly applied to prevent and/or reduce invasion by exotic species in restoration. A system's susceptibility to invasion has been shown to increase in response to altered disturbance regime (e.g., woody encroachment in unburned grasslands) and/or soil resource availability (Burke & Grime 1996; Davis et al. 2000). For example, restoration of native grasslands on abandoned agricultural land can be impeded by years of agricultural fertilizer inputs which have created soil nutrient levels that favor invasive over native plant species (McClendon & Redente 1992; Morghan & Seastedt 1999; Maron & Jeffries 2001; Blumenthal et al. 2003; Averett et al. 2004). The first step in restoring desired native plant species or communities in such areas may therefore require "defertilization" to export or sequester excess nutrients in order to optimize success of native plants that demand lower soil nutrients. For example, the addition of carbon, which promotes microbial immobilization of available and mineralized nitrogen has been shown to reduce colonization and cover of non-native species in prairie restorations (Baer et al. 2003). An integrative restoration approach may also involve physical and biological strategies. For example, carbohydrate supplements along with prescribed fire enhanced native Australian tussock grass restoration (Prober et al. 2005). Baer et al. (2003) found reduced colonization and cover of non-native species in soil amended with carbon to reduce nitrogen availability in a prairie restoration. Thus, carbon addition represents a tool with the potential to alleviate an important filter (i.e., soil nitrogen fertility) on community assembly.

Invasion of a system by exotic species may alter physical, chemical, and/or biological characteristics of the soil. Recognizing feedbacks between invading plant species and soil may be crucial to combating invasion. For example, Vinton and Goergen (2006) documented positive feedback between litter quality and nitrogen mineralization in grassland restoration invaded by Smooth brome (*Bromus inermis*), a species that demands more nitrogen than native prairie grasses. Kulmatiski and Beard (2006) found that soil manipulations (incorporation of activated carbon) influenced competitive interactions between invasive and native plants in the soil by apparent sequestration of allelopathic compounds. Although their manipulations did not result in complete removal of invasive plants from the system, their work demonstrated that solutions for this type of complex restoration challenge require consideration of complex soil processes. This type of targeted manipulation is relatively sophisticated and represents the most exciting future direction of research for soil ecologists and restoration ecologists alike.

Soil Quality as a Concept Guiding Ecosystem Restoration

Our conceptual scheme provides an opportunity for linking a soil's perspective on restoration with monitoring of restoration progress using soil quality indices. Larson and Pierce (1991) defined soil quality as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. In the past 10 years, research on the soil quality concept has proceeded rapidly, with particular emphasis on understanding the role of the soil resource in maintaining environmental quality (Glanz 1995; Pickett et al. 2001) and on the application of the soil quality concept to restoration and management of nonagricultural lands (Sims et al. 1997; Singer & Ewing 2000; Karlen et al. 2001).

Soil quality is specific to each kind of soil (USDA-NRCS 2001); however, measuring dynamic soil properties such as SOM, soil structure, and water-holding capacity can be used both to compare the efficacy of different soil management practices among soils on similar landscape positions with equivalent inherent properties or to track temporal changes on the same soil (Singer & Ewing 2000; Karlen et al. 2001). The results of this assessment can then serve to guide subsequent soil management decisions (Karlen et al. 2001). A variety of user-friendly qualitative and semiquantitative educational materials have been developed for conducting soil quality assessments, including a visual soil assessment procedure (Shepherd 2000), Soil Quality Information Sheets (Muckel & Mausbach 1996), soil health scorecards (Romig et al. 1996), and commercially available soil quality test kits.

Despite some criticism of the notion of soil quality, it should be noted that the soil quality concept was conceived merely as an outreach and assessment tool for evaluating the sustainability of soil management practices and for guiding land use decisions. It should be a suitable way of mediating between research on SEK and managers who may ultimately apply and evaluate the use of this information in restoration projects. Considering the application of the soil quality concept to restoration, Karlen et al. (2003) noted that soil quality assessment will be useful in quantifying both the resistance (defined as the capacity of a system to continue functioning through a disturbance, Pimm 1984) of a soil to degradation and the resilience of a soil to recover following degradation. Given its fundamental grounding in basic principles of pedology and soil ecology, the soil quality concept is inherently embedded in SEK and, therefore, it can serve as a useful tool to guide ecosystem restoration.

Conclusions

Restoration aims to overcome constraints on ecosystem recovery through natural processes to produce resilient ecosystems that are resistant to invasion, capture and use resources efficiently, contain biological complexity needed to function effectively, and provide human-valued services (Ewel 1987; Hobbs 2006). Although the goal of each restoration is defined by stakeholders, selection of targets and assessment of success should be guided by general theory from relevant disciplines and lessons from practice (Hobbs & Harris 2001). With this understanding, we contend that any attempt to facilitate ecosystem recovery from degradation will be improved by applying SEK. Soil ecological perspectives that have emerged in recent decades are integrative and ecosystem oriented because they simultaneously consider the influence of soil physical, chemical, and biological structure on energy flow and material cycling. SEK can be foundational to restoration across multiple ecological scales (from population to whole ecosystem restoration). We propose that the relevance of SEK to restoring degraded systems is determined by the level of soil degradation and the specificity of project goals. When a restoration project aims to restore highly degraded sites to a level of complexity with all former functions of a specified reference condition, very targeted or specific SEK is needed. Success in such instances will require a holistic approach, as even single-factor manipulations can affect soil physical, chemical, and biological properties. Variability in the type of degradation, the specific restoration goals, the time frame in which results are anticipated, and the means by which outcomes are assessed challenge our ability to generalize about approaches that lead to restoration success.

Our conceptual scheme underscores a simple rule of thumb: when complex ecological outcomes are desired, incorporating a more comprehensive SEK is critical to achieve restoration goals. The need for an adequate incorporation of SEK into restoration practice may become even more pressing in future years in the face of global change (globalization of commerce, increased intercontinental flow of biota and materials, climate change, etc.). The prospect of climate change will force difficult decisions on where and what may be restored in ecosystem restoration projects in the future (Harris et al. 2006), and soil ecological considerations may ultimately provide guidance for these decisions. This is evident, given the predicted changes to fundamental characteristics of and processes in soils under different climate change scenarios (Bellamy et al. 2005; Saxon et al. 2005). The implications of this for restoration are only now being investigated (Fox 2007).

Finally, as strong as is the potential for SEK to improve the practice of ecological restoration, the reciprocal influences are also promising. Restoration aims to use ecological theory to improve practice and apply information from practice to improve theory (Palmer et al. 2006). Thus, considering soils in restoration will test our mechanistic understanding of the ecological structure and function of soil in altered environments. Most importantly, this will expose deficiencies in our basic knowledge of soil ecology; as such, restoration practice provides an "acid test" for soil ecology (Bradshaw 1987).

Implications for Practice

- Knowledge of soil should routinely be incorporated into planning and evaluating restoration projects. The level of sophistication required for incorporating SEK depends upon the extent of soil degradation, the goals of the project, and the resilience of the ecosystem, and therefore, all these factors need to be considered in the execution of restoration work.
- When the goals of a restoration project are relatively general ones—e.g., revegetation of a degraded site, without a specific target plant community planned—modest SEK will be needed.
- However, restoring a highly degraded site to a very particular target condition will require extensive SEK.

- The field of soil ecology which has traditionally combined a strong organismal influence with a focus on ecosystem processes should provide a source of knowledge for restoration practitioners, while being itself influenced by knowledge emerging from restoration practice.

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