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A Striking Profile: Soil Ecological Knowledge in Restoration Management and Science

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Abstract

Available evidence suggests that research in terrestrial restoration ecology has been dominated by the engineering and botanical sciences. Because restoration science is a relatively young discipline in ecology, the theoretical framework for this discipline is under development and new theoretical offerings appear regularly in the literature. In reviewing this literature, we observed an absence of in-depth discussion of how soils, and in particular the ecology of soils, can be integrated into the developing theory of restoration science. These observations prompted us to assess the current role of soil ecological knowledge in restoration research and restoration practice. Although soils are universally regarded as critical to restoration success, and much research has included manipulations of soil variables, we found that better integration of soil ecological principles could still contribute much to the practice of ecosystem restoration. Here we offer four potential points of departure for increased dialog between restoration ecologists and soil ecologists. We hope to encourage the view that soil is a complex, heterogeneous, and vital entity and that adoption of this point of view can positively affect restoration efforts worldwide.

Key words: land use legacies, restoration, soil, soil ecology, soil fauna.

Background

Soil ecology blends knowledge of physical, chemical, and biological processes and properties to better understand and manage ecosystems, communities, and species' functions and interactions. The interplay between aboveground and belowground structure and function holds great relevance to the maintenance of native biodiversity and viable ecosystems (Wardle 2002), so the marriage of restoration and soil ecological perspectives holds great promise. Indeed, restorationists have long appreciated the importance of soils, in spite of the fact that terrestrial restoration science has focused primarily on establishing aboveground plant communities. Here we discuss the current state of these interactions and attempt to identify areas where greater appreciation for the parallel interests of the two disciplines could advance both restoration successes and soil ecological knowledge.

In October 2005, an international group of soil ecologists gathered on the campus of the University of Georgia (UGA) to participate in a special symposium celebrating the retirement of Prof. David C. Coleman from the Institute of Ecology at UGA. During this symposium, several participants discovered a common interest in restoration ecology and decided to conduct a detailed evaluation of how the discipline of soil ecology had contributed to progress in the practice of Restoration Ecology. Toward this end, a small group met in Chicago at DePaul University for a workshop, and a half-day symposium was held at the Ecological Society of America meetings in Memphis (2006). These efforts helped the group to focus their questions and further demonstrated that the topic was of interest to a large number of individuals from a broad spectrum within the ecological research community. Momentum from these efforts ultimately led to the planning and execution of a larger conference on the subject of interfaces between soil ecology and restoration ecology held at DePaul University in Chicago, Illinois, U.S.A., from 18 to 20 December 2006. With more than 150 participants, the audience consisted of scientists, land managers, and restoration practitioners. The articles in this special section represent a substantial fraction of the presentations made at the conference in Chicago.

The workshop, symposium, and conference all were loosely organized around the basic question of whether or not Soil Ecology and Restoration Ecology were making full use of their accumulated wisdom to accomplish restoration goals. We retooled a question based on Bradshaw's (1983) famous proposition: "If restoration is the acid test of ecology, what is the pH of our soils knowledge?" Most of the original organizers could be best described as soil ecologists (i.e., not restoration ecologists), and we proceeded with the possibly naïve view that in practice, restoration ecology employs a simplistic approach to soil (soil = medium for plant growth). We based this view on observations by Ruiz-Jean and Aide (2005) that success in

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restoration ecology is most often measured as establishment of a target plant community (diversity, cover, structure, etc.). Clearly, this approach is unsatisfying for soil ecologists who view soil as a dynamic and vital entity. Indeed, soil ecologists view degraded soils as being worthy of restoration in and of themselves and might subscribe to the point of view that ecosystem restoration cannot be considered complete unless the full complement of soil biota (microbes, invertebrates, and plants) is present and functioning. Thus, although soil ecologists should have much to offer to restoration science, it is not clear that they have been involved to an appropriate degree to date. Some notable exceptions to this general pattern include the work of a few groups working with mycorrhizal fungi as a way to encourage plants targeted for restoration (Fig. 1B), but much of the other chemical, physical, and biological aspects of soil have been overlooked or only approached as single factors at best.

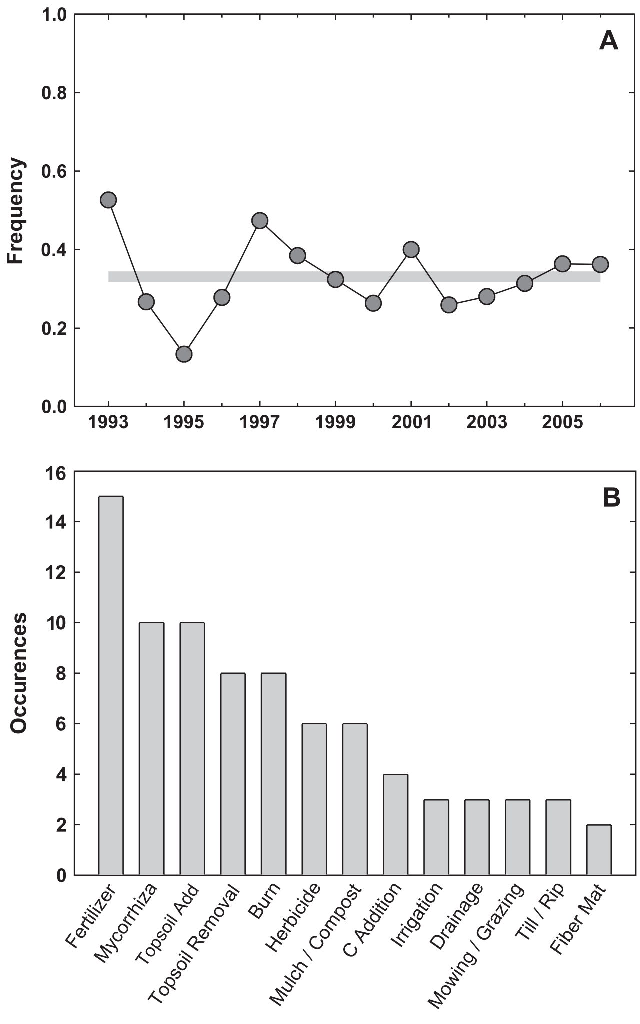

Figure 1. Citation statistics for articles appearing in *Restoration Ecology* from 1993 to 2006. (A) Frequency that soil-related terminology was included in titles of article. The line represents the mean proportion over the entire period. (B) Soil-related manipulations involved in studies appearing in *Restoration Ecology* from 1993 to 2006.

Digging Deeper

As a rough estimation of how soil knowledge is used in restoration, we surveyed the articles published in *Restoration Ecology* from 1993 to 2006 (vols. 1–14). Soil terminology appears in the titles of roughly one-third of the empirical studies (Fig. 1) during that period, demonstrating a central role of soil in restoration management and science. Review of terrestrial studies published in *Restoration Ecology* revealed that soil-centric information is used, to varying degrees, to describe prerestoration site conditions, manipulative restoration treatments, and the responses and recovery following restoration actions (Table 1).

Thus, when delving further into the question of whether soil ecology is considered in restoration efforts, we happily discovered that much good work has been done. In light of the original motivations for our deliberations on the subject, the frequency and breadth of soil-related material in the restoration literature must be seen as a good thing. Still, our ultimate conclusion was that much more can be gained from a better incorporation, a priori, of soil-based information when restoration plans are formulated. We offer the following points as a critique of what has gone before, with some very brief suggestions as to how the existing efforts might be improved.

(1) Healthy soils are alive: Documented cases of edaphic change associated with soil fauna activity (e.g., influence of termites on soil porosity and infiltration) were scarce in the restoration context. Clearly, long-term monitoring of restoration projects should yield valuable information about how soil health and soil quality may be expected to respond under differing restoration conditions. With few exceptions, soil fauna have been used only as indicators of soil recovery but have not been fully exploited in terms of their ability to act as agents of restoration. Experimental additions of soil fauna to soils where they are absent should be further explored, and articles in this special section deal specifically with the prospect of using soil macrofauna in restoration. Snyder and Hendrix (2008) provide a review of how some faunal groups have been used in the restoration context, and Butt (this issue) gives a detailed and practical evaluation of efforts to use earthworms in several restoration and reclamation projects in the United Kingdom.

(2) Soils have history: Published studies commonly characterized change in soil properties over seasons or several years, rather than development of soil attributes in response to decade-scale alteration in soil structure, organic matter accumulation, nutrient leaching, or hydrologic fluctuations. Furthermore, conclusions from restoration experiments often relied upon

Table 1. Soil-related information contained in terrestrial restoration studies published in *Restoration Ecology* from 1993 to 2006 (vols. 1–14).

Aspect of Study	*How Soils Information Is Used*
Site conditions	Comparisons between candidate restoration and reference sites were a typical index of soil degradation and were used both to identify obstacles to restoration and to define baseline conditions for monitoring project success. The most frequent form of soil degradation was nutrient enrichment in former agricultural soils and in sites affected by nutrient loads in atmospheric deposition, run-off, or groundwater.
Restoration treatments	Inorganic fertilizer was the most prevalent soil treatment both at the field and the individual plant scales; mulch and compost of various types also were used to improve soil fertility. Mycorrhizal inoculation of seedlings via spore or topsoil additions was the second most common soil amendment. Salvage, storage, and application of topsoil to field studies were typical for revegetating mine lands, road corridors, and burned areas. Carbon addition, either as sawdust and/or as sucrose, was employed to reduce plant-available soil nitrogen and favor native species.
Edaphic responses	Total soil nitrogen and organic matter stocks, followed by indices of plant nutrient availability were the most frequently measured soil responses. Soil chemistry, water relations, microbial activity, and fungal symbionts were all equally well represented. A wide variety of invertebrate soil organisms (nematodes, microarthropods, and earthworms) were used as bioindicators of ecosystem recovery or health.

unmeasured soil responses to restoration treatments, climate fluctuation, historic disturbance (e.g., herbivory and tillage), or species effects (e.g., shrub and N-fixer encroachment) to explain findings that could not be attributed to experimental treatments. Explicit consideration of previous land use and the legacies of herbicides, nutrient and metal accumulation, changes in soil physical properties, compaction, fire, grazing, and other perturbations on soil processes should lead to more effective restoration efforts. The influence of past land use and other extrinsic factors is perhaps most notable in urban soils targeted for restoration, and Pavao-Zuckerman (2008) provides an excellent theoretical framework from which to approach this difficult problem in urban systems. Another fine example of the importance of such legacy effects is found in Anderson (2008) where the history of land management (tillage history, nutrient management, and hydrology) was more influential to the experimental outcome than the variable that was the object of the original experiment (time since restoration initiated).

(3) Soils are heterogeneous: The resolution of soil classification included in many studies (i.e., USDA Soil Taxonomy Soil Series) may overlook important fine-scale spatial variability. Greater detail regarding soil heterogeneity, such as that occurring along topographic gradients and across habitat boundaries, can assist in the design of restored ecosystems that closely mimic the belowground function and structure of reference areas. Several of the contributions to this special section address the issue of soil heterogeneity and how it may inform different approaches to restoration. Grimley et al. (2008) describe how fine resolution measurements and mapping of one soil variable (magnetic susceptibility) can greatly improve decision-making with regard to selection of appropriate vegetation for given sites. Barton et al. (2008) used a similar approach, measuring soil variables to guide decisions about expensive restorative hydrological manipulations, and showed that soil variables could be used to accurately predict sites that did not require such manipulations. Wells et al. (2008) describe results from a fine-scale sampling and characterization of soils derived from sediments as well as the original soils underlying these sediments. They clearly demonstrated in this work that the spatial heterogeneity of resources in the sediments was very different from that of underlying soils and conclude that these differences must be taken into account when restoring vegetation more characteristic of the heterogeneous underlying soils.

(4) Soil functions integrate physical, chemical, and biological components: Restoration Science currently approaches soil knowledge in a piecemeal fashion and is often fragmented along disciplinary lines (e.g., nutrient, biotic, hydrologic). Researchers aiming to promote the relevance of soil science to ecosystem restoration must highlight cases where integrated assessment of belowground processes yielded practical knowledge resulting in successful restoration manipulations or monitoring. Because soil systems are complex and imperfectly understood, and because restorations are often situated in soils that have no reasonable analog in the natural world, experimentation is the only avenue to improved decision-making. Multifactor experiments such as the one by Iannone and Galatowitsch (2008) are essential to gaining full appreciation for the interacting variables that can prove to be critical to the ultimate success of a restoration. In cases where soils are more seriously degraded, such as the system detailed in Seo et al. (2008),

straightforward tests of which plant species will grow and ameliorate soil conditions are also needed.

The articles making up this special section will hopefully provide a starting point for further discussions of how soil ecological considerations can improve the planning and ultimate outcome of restoration projects. By way of framing these issues, Heneghan et al. (2008) offer a review and theoretical evaluation to make a case for better incorporation of soil ecological knowledge into restoration projects, whereas Montgomery and Eames (2008) provide a real-world example of one restoration project that might have been more successful, had such knowledge been applied at its outset.

The primary message we think will emerge from all these contributions is that soil makes a difference to restoration efforts—soil matters. Although this message may seem self-evident, an important subtheme that runs through all these articles is the remarkable variety of ways in which soil can "matter" to restoration. In other words, the contextual dependency of soil's importance to restorations cannot be ignored. The article by Eviner and Hawkes (2008) is a clear and concise statement of the problem of soil context dependency, and the authors offer suggestions as to the potential best way forward. Indeed, this context dependency may partially explain the large fraction of titles falling into the "Case Studies" category, but with every positive identification of situations where soils made a difference in restoration, we make a positive increment in our ability to clear obstacles in the way of success. Finally, it is notable that the relatively small number of experimental studies represented in this special section is reflective of the broader demographic of soil-related restoration studies. There have been too few rigorous experimental manipulations of soil factors, which incorporate the real complexity of soil systems. We are hopeful that this situation will change in the near future, and we hope that this special section may serve as a starting point for investigations along these lines.

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LITERATURE CITED

Anderson, R. C. 2008. Growth and arbuscular mycorrhizal fungal (AMF) colonization of two prairie grasses grown in soil from restorations of three ages. Restoration Ecology **16:**650–656.

Barton, C. D., D. M. Andrews, and R. K. Kolka. 2008. Evaluating hydroperiod response in restored Carolina Bay wetlands using soil physicochemical properties. Restoration Ecology **16:**668–677.

Bradshaw, A. D. 1983. The reconstruction of ecosystems. Journal of Applied Ecology **20:**1–17.

Butt, K. R. 2008. Earthworms in soil restoration: lessons learnt from United Kingdom case studies of land reclamation. Restoration Ecology **16:**637–641.

Eviner, V. T., and C. V. Hawkes. 2008. Embracing variability in the application of plant–soil interactions to the restoration of communities and ecosystems. Restoration Ecology **16:**713–729.

Grimley, D. A., J. Wang, D. A. Liebert, and J. O. Dawson. 2008. Soil magnetic susceptibility: a quantitative proxy of soil drainage for use in ecological restoration. Restoration Ecology **16:**657–667.

Heneghan, L., S. Miller, S. Baer, M. A. Callaham Jr, J. A. Montgomery, M. A. Pavao-Zuckerman, C. C. Rhoades, and S. Richardson. 2008. Integrating soil ecological knowledge into restoration management. Restoration Ecology **16:**608–617.

Iannone, B. V. III, and S. M. Galatowitsch. 2008. Altering light and soil N to limit *Phalaris arundinacea* reinvasion in sedge meadow restorations. Restoration Ecology **16:**689–701.

Montgomery, J. A., and J. M. Eames. 2008. Prairie wolf slough wetlands demonstration project: a case study illustrating the need for incorporating soil and water quality assessment in wetland restoration planning, design and monitoring. Restoration Ecology **16:** 618–628.

Pavao-Zuckerman, M. A. 2008. The nature of urban soils and their role in ecological restoration in cities. Restoration Ecology **16:**642–649.

Ruiz-Jean, M. C., and T. M. Aide. 2005. Restoration success: how is it being measured? Restoration Ecology **13:**569–577.

Seo, K. W., Y. Son, C. C. Rhoades, N. J. Noh, J. W. Koo, and J. Kim. 2008. Seedling growth and heavy metal accumulation of candidate woody species for revegetating Korean mine spoils. Restoration Ecology **16:**702–712.

Snyder, B. A., and P. F. Hendrix. 2008. Current and potential roles of soil macroinvertebrates (earthworms, millipedes, and isopods) in ecological restoration. Restoration Ecology **16:**629–636.

Wardle, D. A. 2002. Communities and ecosystems: linking the aboveground and belowground components. Princeton University Press, New Jersey.

Wells, A. J., N. J. Balster, S. VanWychen, and J. Harrington. 2008. Differences in belowground heterogeneity within a restoration of a dewatered reservoir in southwestern Wisconsin. Restoration Ecology **16:** 678–688.