Synthesis

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The chapters of Section 5 support the fundamental role that soil biota play in sustaining soil structure and nutrient cycling as the foundation for nearly all ecosystem services while illustrating the challenges of documenting explicit, consistent relationships. Provisioning services, including crop production, were the focus of the majority of the studies cited in this section and, as Cavigelli *et al.* point out, a high proportion of the management system comparisons are limited to conventional tillage against some form of organic or conservation tillage-based system. Despite these inherent limitations of the existing literature, a number of lessons can be drawn. Five that are particularly significant were each cited in at least two of the chapters: 1) the importance of spatial and temporal context for interpreting soil biota-sustainability relationships, 2) the importance of systematic approaches, common methods, and protocols to study soil biota—sustainability relationships, 3) the value of long-term studies for identifying and validating functional relationships, particularly where chronic, cumulative, and acute disturbances are involved, 4) the potential value of local knowledge for identifying, documenting, and monitoring these relationships, and 5) the extent to which hysteresis must be considered to understand and predict the potential contribution of soil biota to resilience and restoration.

(1) *Context is critical.* Cavigelli *et al.* conclude that, "management impacts on ecosystem services and soil biodiversity are often complex such that responses may be subtle and vary with soil type, climate, ecosystem, taxonomic and/or functional group, and ecosystem service." This statement can be extended to include soil biodiversity impacts on ecosystem services. The chapter by Van Oost and Bakker adds temporal context, and specifically the stage of soil degradation, as an additional factor that must be considered when interpreting soil biota—sustainability relationships. Several studies cited by Grandy *et al.* emphasize the fundamental importance of spatial context, and in particular soil texture. A lack of basic soil characterization data has been, and continues to be, a significant factor limiting meta-analyses of multiple datasets.

(2) *A systematic approach is needed.* The diversity of methods to quantify ecosystem services and soil biota sometimes seems to rival the diversity of the organisms themselves. While there are often good reasons for the selection or development of a new or esoteric method, in many cases our decision not to apply an existing method is limited only by ego or simply an unwillingness to make the time to identify common methods, and to recognize which modifications make it impossible to compare datasets that purportedly include the same parameter. National to regional efforts such as the African Soil Information System (AfSIS) cited by Barrios *et al.* should increase the availability of standardized information in the future.

(3) *Long-term studies.* Nearly all of the chapters cited the value of long-term studies involving multiple treatments for teasing apart complex relationships between management, soil biota, and ecosystem services in the longer-term. As Grandy *et al.* point out, long-term studies are particularly important for understanding the critical soil properties and processes that control ecosystem resilience and recovery. Chronic disturbances, including those associated with climate change and nitrogen deposition, both affect and are mediated by soil biota. These complex interactions are nearly impos-

sible to understand without longitudinal data. "Novel ecosystems" represent another case where long-term studies are essential as it is, by definition, impossible to substitute space-for-time experimental designs for new long-term studies. Baer *et al.* define these novel ecosystems as "self-perpetuating communities that contain no historic analog in terms of species composition and historic function" and "represent a self-sustaining stable state under new biotic and abiotic conditions." While the permanence of "stable states" continues to be debated by ecologists, the challenge of understanding ecosystems in the context of novel conditions is now widely accepted and forms a research priority a sustainable future.

(4) *Local knowledge and local communities can contribute to the identification, documentation and monitoring these relationships.* Both Barrios *et al.* and Karlen cite the value of farmers' knowledge in documenting relationships between management practices and soil health. New technologies, including GPS-enabled camera phones with data-input and transmission capabilities now allow individuals to share site-specific knowledge and information. With a limited amount of training in soil characterization (e.g. depth, sandiness, and stickiness), the information contributed by farmers could be increased beyond what is already possible by linking their geolocated observations to digital elevation models (for slope, slope shape, landscape position, and aspect), greenness indices that provide information on phenology and production, and other geospatial data derived from remote sensing imagery.

(5) Finally, *understanding hysteresis is key to understanding and predicting the potential contribution of soil biota to resilience and restoration.* Rangeland ecologists, in particular, have now concluded that stable states represented by a single climax plant community are the exception rather than the rule, and that hysteretic dynamics are to be expected. The soil biotic communities associated with transitions among states, and plant communities within states, are similarly complex and dynamic. While general rules are elusive, a number of studies have documented significant shifts in soil biotic communities associated with aboveground dynamics.

There is a virtually infinite need for research, and it is clearly impossible to always apply the comprehensive set of six steps necessary to confirm mechanistic relationships (listed by Barrios *et al.*). We argue that research will need to become increasingly strategic, focusing on the short- and long-term dynamics of key processes rather than simply attempting to establish the importance of particular groups of organisms. Studies must also be designed to allow multiple sources of spatial and temporal variability to be considered, if not addressed. We believe that this approach could also increase our understanding of key feedbacks and interactions between soil biota, pests, diseases, and plant nutrient and water status and, ultimately, plant and animal production.