Why SoilScience must embrace an ecosystems approach

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Soils provide vital functions for society (Blum, 2006). They support and sustain our terrestrial ecosystems; grow our food, feed, fiber, and wood; regulate the atmosphere; filter water; recycle waste; preserve our heritage; act as an aesthetic and cultural resource; and provide a vital gene pool and biological resource from which many of our antibiotics have been derived (D'Costa et al., 2006). Despite their role as the biogeochemical engine of the earth's life support system, soils are often perceived as failing to attract the attention of policymakers and society at large (Bouma, 2001), especially with regard to soil protection and sustainability. While water and air influence our health because of direct consumption, the connection between human health and soils is often more subtle and still is not fully understood.

As we deal with global change and increasing populations, however, soils are increasingly being linked to human health and well-being, whether by the release of arsenic to groundwater by redox cycling in the soils of Southeast Asia (Polizzotto et al., 2008), by the impact of soil moisture on the spread of malaria (Patz et al., 1998), or even the exacerbation of fatal heat waves in Europe due to reduction of the soil moisture buffer (Seneviratne et al., 2006). As we understand the significance of managing the earth's soils, not only for food production but increasingly for environmental regulation and earth system functioning, it becomes crucial that we define their value in suitable terms for policymakers, land managers, and future generations. It is therefore vital that soil scientists are actively involved in the development of frameworks that convey the societal value of soil functions in terms of both human well-being and the sustainment of the earth's life support systems and the diversity of life the planet holds.

Research into the concept of soil quality is an ongoing effort to generate indicators of the performance of soils that can inform policy (Doran and Parkin, 1996). In the European Union (EU), the Driving Forces–Pressures–States–Impacts–Responses framework is widely used to identify links between policy and its impact on natural resources, including soils (Blum et al., 2004). An ecosystems approach goes further, however, by valuing natural resources and the benefits we obtain from them in terms of the goods and services that they provide to society (Millennium Ecosystem Assessment, 2005). Westman (1977) first proposed that the value of ecosystems and their benefit to society should be incorporated into policy making. This con-

Soils provide a vast store for soil carbon, which is important for regulating climate. *Photo courtesy of David Robinson.*

cept was further developed by Daily (1997) and Costanza et al. (1997a) and their sources. Since the release of the Millennium Ecosystem Assessment report (Millennium Ecosystem Assessment, 2005) and the stark warnings it contained, governments and policy-making bodies have begun adopting the idea of an ecosystems approach to pursue sustainability and incorporate resource life support value into decision making (e.g., Department for Environment, Food and Rural Affairs, 2007). These new directions would be strengthened by incorporation of soils into these frameworks, capitalizing on developed and emerging soil science concepts and thus conveying the importance and value of soils to decision makers. The EU has already identified soil ecosystem services as a priority research area in the European Union Soil Thematic Strategy. The EU is financing a number of projects that incorporate soil ecosystem services, including the SoilTrEC project (Banwart, 2011), the SOIL SERVICE project, and the EcoFINDERS project.

Soil quality and health (Karlen et al., 1997; Singer and Ewing, 2000), along with the emerging concept of "soil change" (Tugel et al., 2005), are frameworks that were recently developed in soil science. Concurrently, ecosystem services and natural capital frameworks have emerged from ecology and economics (Daily, 1997; Costanza et al., 1997b). In Fig. 1, we demonstrate the interrelationships among these concepts, each of which are vital for conveying the importance of soils to society. The soil resource is composed of material stocks such as minerals, C, water, air, and nutrients, with important characteristics that we identify through soil formation processes such as horizonation, aggregation, and colloid formation (Churchman, 2010). Soil stocks constitute the soil natural capital (Robinson et al., 2009; Dominati et al., 2010a) on which processes act. These lead to flows and transformations, resulting in changes in the stocks through interactions with the wider environment. Ecosystem services result from the flows of materials and energy. These include outflows of C in food, feed, or fiber; inflows of C that aid climate regulation; the contribution of soils to water regulation and filtering; and waste disposal and recycling. Building or improving the soil natural capital is an important aim, contributing to soil resilience and maintaining balance in the provision of ecosystem services. It is important that our focus on ecosystem services does not ignore the important role of natural capital or result in the provision of services at the expense of changes in

Soils play an important role in supporting the provisioning of food, feed, and fiber. *Photo courtesy of David Robinson.*

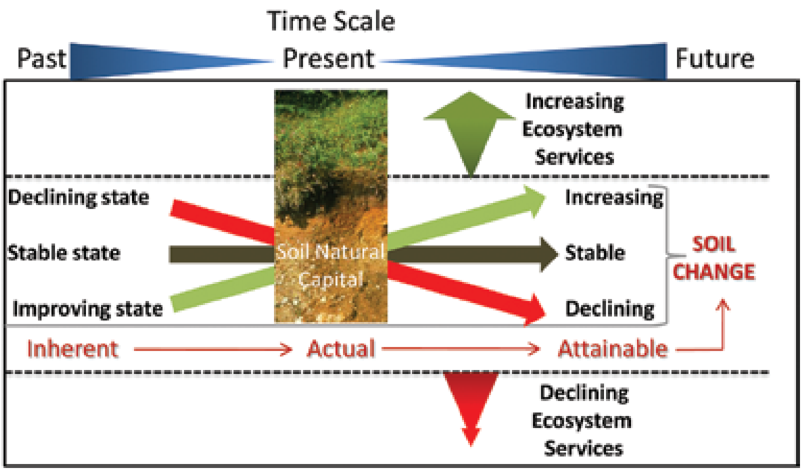

Fig. 1. The temporal balance between soil natural capital and ecosystem goods and services supporting the concept of "soil change." The ascending light green arrow through soil natural capital indicates capital improvement, whereas the descending red arrow is capital degradation. With time, ecosystem services will diminish if capital is degraded; conversely, building capital may increase the soil's capacity to deliver goods and services. This is a broad generalization because building capital may also result in some disservices. The end goal is a sustainable balance of capital and ecosystem services.

the inventory value of natural capital stocks that could be unsustainable.

The soil quality framework (Karlen et al., 1997) provides an indicator of the state of the soil natural capital stocks at any given point in time, while the concept of soil change (Richter and Markewitz, 2001; Tugel et al., 2005; Richter et al., 2011) recognizes that soils are continually evolving and transforming, especially within anthropogenic time scales (Fig. 1). The current state of the soil is termed the actual state, while its inherent state might be thought of as its undisturbed state, and its future state is that which can be attainable. Last century, much of soil science emerged from an interest in understanding how soils formed in relatively undisturbed environments during long periods of time. Soil change recognizes the dynamic response of soils to anthropogenic activity in much the same way that we study climate and land use change. The soil science emphasis on gradual change during pedogenesis can be counterproductive in discussions with policymakers, who can interpret gradual change as unimportant within their time in office. Conveying the dynamic nature of soils, and that change occurs on time scales that are relevant to policymakers and their generation, is an important challenge for soil science. Figure 1 shows that all of these concepts are complementary and contribute to both our understanding and the way we convey the contribution and value of soils to human beings and their societies.

Given the importance of developing these approaches for soil science, there are significant challenges that can be identified to combine these concepts into a useful framework. We have identified four areas that require further research, development, or synthesis to provide tools for bridging the science–policy divide:

- developing a framework;
- quantifying the soil resource, stocks, fluxes, transformations, and identifying indicators;
- valuing the soil resource for its ecosystem services;
- developing management strategies and decision support tools.

Developing a Framework

Daily et al. (1997) presented perhaps the first attempt to identify distinct soil ecosystem services (Table 1, next page). Although this has been expanded by others (Wall, 2004; Andrews et al., 2004; Weber, 2007; Clothier et al., 2008; Dominati et al., 2010a; Dominati, 2011), to date there has been no accepted ecosystem service framework for soils. More broadly, there is still much discussion and refinement of the ecosystem services framework in general. Fisher et al. (2009) provided a recent overview of how ecosystem services are defined, showing that the literature has no commonly accepted consistent definition. This is something that they, and others (Boyd and Banzhaf, 2007; Wallace, 2007), argued is required to turn a conceptual framework into an operational system of accounting. This represents a challenge for soil science but also an opportunity to engage at this stage to shape the broader framework.

One aspect of framework development that is of particular importance for soil science is the treatment of soil natural capital (Robinson et al., 2009; Dominati et al., 2010a), given that soil is perhaps most obviously conceptualized as a stock that contributes to final ecosystem services primarily through supporting processes. The key to sustainability is ensuring that ecosystem services are not derived at the expense of the soil natural capital; for instance, conversion to intensive agriculture without some form of regeneration, or a more extreme example would be strip mining without restoration. Perhaps some of the biggest challenges we face in soil science are preventing soil degradation and erosion in an increasingly populous world. To date, natural capital has been underemphasized in the ecosystem approach, where the focus has been more on flows of ecosystem services rather than on the stock of natural capital from which they are derived. Approaches that incorporate natural capital have been proposed by Palm et al. (2007), with a new comprehensive typology proposed by Robinson et al. (2009) based on mass, energy, and organization (Table 2). Recognizing the important contributions of both approaches, Dominati et al. (2010a) attempted to present a synthesis of both the ecosystem services and natural capital approaches (Robinson and Lebron, 2010; Dominati et al., 2010b). Continued efforts are required to build an ecosystems framework for soils that properly integrates ecosystem services and natural capital and links with other efforts under the general ecosystem services approach.

Quantification

The next challenge is to identify the appropriate indicators and metrics for evaluating natural capital and ecosystem goods and services. Based on the natural capital framework, one approach is to evaluate soil stocks and determine how they change with time (Bellamy et al., 2005; Emmett et al., 2010). This is one challenge for profile-scale soil architecture because soil structural change may not be explained by a reductionist approach (de Jonge et al., 2009). Furthermore, measuring the change in soil stocks with time is not trivial due to changes in soil bulk density (Lee et al., 2009). Perhaps the only way to truly estimate changes in stocks is to measure entire soil profiles using soil cores down to either lithic or paralithic contacts. Other opportunities that may exist with regard to soil architecture include methods to evaluate soil depth across landscapes and determining the depth distribution of soil properties, particularly bulk density and porosity, to determine whether they transition smoothly or if there is an abrupt change due to horizonation.

An alternative approach to quantifying stocks is to measure the fluxes into and out of the soil as a means to estimate changes in the magnitude of the stocks. This still requires a one-time estimate of the stocks to determine a baseline for natural capital. This approach is also not trivial because closing the mass balance is challenging, although some would argue that all that is needed is to know the relative changes. This approach may be more suitable for certain properties under specific boundary conditions, such as for determining C fluxes from peatlands and for looking

Table 1. Soil ecosystem services identified by Daily et al. (1997), categorized according to the Millennium Ecosystem Assessment (2005) classification of ecosystem services. Note that habitats and gene pool could be regarded as natural capital stocks, rather than ecosystem service flows.

Classification	Services
Supporting	renewal, retention, and delivery of nutrients for plants
	habitat and gene pool
Regulating	regulation of major elemental cycles
	buffering, filtering, and moderation of the hydrologic cycle
	disposal of wastes and dead organic matter
Provisioning	building material
	physical stability and support for plants
Cultural	heritage sites, archeological preserver of artifacts
	spiritual value, religious sites, and burial grounds

Table 2. A summary of the soil natural capital typology adapted from Robinson et al. (2009). This is not an exhaustive list but a guide for classification.

Natural capital	Measurable or quantifiable soil stock
Mass	
Solid	inorganic material: mineral stock and nutrient stock
	organic material: organic matter and C stocks and organisms
Liquid	soil water content
Gas	soil air
Thermal energy	soil temperature
Biomass energy	soil biomass
Organization–entropy	
Physicochemical structure	soil physicochemical organization, soil structure
Biotic structure	biological population organization, food webs, and biodiversity
Spatiotemporal structure	connectivity, patches, and gradients

at the impacts of different land uses on soil natural capital stocks. Another potential approach is to measure proxy parameters when a stock or flux is hard to quantify (Dominati, 2011). For example, the number of workable days can be used as an indicator for susceptibility to soil compaction. An important contribution is therefore to determine how to best assess "soil change" with regard to soil stocks, fluxes, or transformations. Much of the existing monitoring at national scales tends to emphasize direct measurement of soil stocks, as done in the UK's Countryside Survey (Emmett et al., 2010).

Soil indicators are parameters that reflect the state or function of the soil system. These indicators are relatively easy to measure and are widely used to assess soil quality and health (Doran and Parkin, 1996; Karlen et al., 1997), although there is still much discussion with regard to which are the most appropriate. The existing indicators need to be reviewed and, as appropriate, linked to functional outcomes at the field, farm, or catchment scale using a soil natural capital and ecosystem services approach. The outcomes of such a review will increase the value of the indicators to land managers and policymakers by providing them with the ability to assess whether land use and land use changes align with environmental policy statements and sustainability principles. The indicator approach is widely used in other areas for decision making, for example, the economic indicator gross domestic product (GDP).

Similarly, developing internationally recognized indicators with universally accepted measurement methods and protocols may enable comparison at national and continental scales. This could be, for example, for soil C stocks and changes for the Kyoto Protocol or C footprinting for products (British Standards Institute, 2011). In addition, we should consider an indicator framework that will allow us to assess the function of anthropogenic or reclaimed soils. The challenge is then to use existing indicators of soil quality while shifting their focal point toward ecosystem services.

Valuation and Tradeoffs

There will always be tradeoffs among ecosystem services, manufactured goods, and other sources of human well-being. We implicitly ascribe relative values to them whenever we choose between alternative actions such as deciding whether to use land for production agriculture or

Much of our cultural heritage is preserved by soils, to be uncovered by later generations. *Photo courtesy of David Robinson.*

a wildlife reserve. To understand and inform these decisions, it can be helpful to render these values explicit, and this is what environmental valuation seeks to do. By valuing ecosystem services in common units, usually, but not always, monetary, it is anticipated that the contribution of ecosystems, including soils, to human well-being will be recognized in societal decision making (Pearce et al., 2006). Otherwise, we tend to consider only those goods and services that are currently traded in markets (Edwards-Jones et al., 2000).

As well as assisting with specific decisions, it is hoped that environmental valuation will lead to the "greening" of existing economic indicators such as the GDP, which at present only incorporates goods and services traded in markets or supplied by governments, ignoring other sources of human well-being such as flood control and C sequestration that are incompletely valued by markets (Organization for Economic Co-operation and Development, 2011).

In addition, the GDP, which is a measure of the flow of goods and services, does not take into account the depreciation of natural capital or resource stocks. While some national accounting measures are estimated net of depreciation or degradation of manufactured capital, the depreciation or degradation of natural capital is generally ignored. Such externalities need to be internalized to achieve green growth. Developing a coherent ecosystem services–natural capital framework is essential for the proper valuation of the environment, and it is imperative that soil scientists participate in this important process.

Decision-Support Tools

While the methods of environmental valuation are well established and case studies abound, the practical challenge of valuing soil ecosystem services and the natural capital that produces them is formidable. As a result, the feasibility of systematically incorporating environmental values into existing economic decision-making tools (e.g., cost–benefit analysis) and accounting systems (e.g., the GDP) has yet to be fully understood. This may pose a substantial challenge to approaches by which society currently makes decisions. The development of economic tools for decision making may not be seen as the remit of soil science, but soil scientists must engage in this process. One reason is that

Soilscapes are an important contributor to cultural services. *Photo courtesy of David Robinson.*

these decision tools need strong input from a soil management perspective, especially with regard to land use. A prerequisite, and current research challenge, is understanding the interaction among land management, land use, and soil change. Already, soil science has made important contributions by developing decision-support tools for land management (Andrews et al., 2004; Tugel et al., 2008). The challenge now is to evolve many of these tools or decision-support methods so that they can be used by many sectors of society for wider policy decisions and be applied to different types of ecosystems rather than solely for production agriculture. Attempts to develop such tools for ecology are now emerging, such as Invest (Nelson et al., 2009); integration with soil science is essential. As a community, soil scientists must develop information, including soil spatial information and soil functioning data that are readily integrated into new decision-support tools that can be used by other communities such as ecology and hydrology.

How Should Soil Science Respond to This Challenge?

We believe that soil science should embrace the opportunity to promote the value of soils for society and human well-being so as to demonstrate that the soil's life support functions need to be properly recognized within the ecosystems approach. This requires action by the soil science community to develop the soils component of the ecosystems approach by:

1. creating the appropriate frameworks to determine the natural capital and intermediate and final goods and services supplied by soils that benefit human well-being, maintain the earth's life support systems, and promote biodiversity;
2. identifying appropriate measurement and monitoring programs with agreed metrics to develop the evidence base on the "state and change" of soil natural capital and the ecosystem services that flow from it;
3. developing the means to value soils, which can feed into the frameworks being developed in other disciplines, and where possible develop synergy with existing national accounting frameworks such as GDP and state-of-the-environment reporting; and
4. engaging in the development of decision-support tools that incorporate "soil change" and that will enable the most informed comparison of tradeoffs in the decision-making process, cognizant of the enormous practical challenges this implies.

Ecologists began to move forward with framework development and, in doing so, recognized the vital role that soils play (Daily et al., 1997; Wall, 2004; Millennium Ecosystem Assessment, 2005). By embracing this first step, the soils community can infuse into this approach the wealth of information and knowledge developed during more than 100 years of soil science and benefit from the resulting synergies with other disciplines. Involvement of multiple disciplines is needed to develop and agree on a way forward and then apply this to the ecosystems approach. Enormous opportunities will be generated by the framing of future soil science research needs in the context of contributing to an ecosystems approach that can inform policy and protect the vital functions of soil that support human well-being, the earth's life support systems, and the diversity of life on this planet.

Interested in this topic? Check out related articles in a special section on Soil Architecture and Function in the February 2012 issue of *Vadose Zone Journal* at www.soils.org/publications/vzj/tocs/11/1

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