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Natural Capital, Ecosystem Services and Soil Change: Why Soil Science must Embrace an Ecosystems Approach.

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Abstract

Soil is part of the Earth's life support system, but how should we convey the value of this and of soil as a resource? Consideration of the ecosystem services and natural capital of soils offers a framework going beyond performance indicators of soil health and quality, and recognizes the broad value that soil contributes to human wellbeing. This approach provides links and synergies between soil science and other disciplines such as ecology, hydrology and economics, recognizing the importance of soils alongside other natural resources in sustaining the functioning of the Earth system. In this article we articulate why an ecosystems approach is important for soil science in the context of natural capital, ecosystem services and soil change. Soil change is defined as change on anthropogenic time scales and is an important way of conveying dynamic changes occurring in soils that are relevant to current political decision making time scales. We identify four important areas of research, 1) framework development; 2) quantifying the soil resource, stocks, fluxes, transformations and identifying indicators; 3) valuing the soil resource for its ecosystem services and 4) developing decision support tools. Further we propose contributions that soil science can make to address these research challenges.

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). Yet despite their role as the biogeochemical engine of the Earth‘s life support system, soil scientists often perceive that soils fail to attract the attention of policy makers 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. However, as we deal with global change and increasing populations, 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 S.E. 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 its value in suitable terms for policy makers, 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 sustaining 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, the Driving forces, Pressures, States, Impacts, Responses (DPSIR) framework is widely used to identify links between policy and its impact on natural resources including soils (Blum et al., 2004). However, an ecosystems approach goes further by valuing natural resources and the benefits we obtain from them in terms of the goods and services that they provide to society (MEA, 2005). Westman (1977) first proposed that the value of ecosystems and their benefit to society should be incorporated into policy making. This concept was further developed by Daily (1997) and Costanza et al. (1997a) and the references therein. Since the release of the Millennium Ecosystem Assessment report (MEA, 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. Anon. 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 European Union (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 incorporating 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, the ecosystem services and natural capital frameworks have emerged from ecology and economics (Daily 1997, Costanza et al., 1997b). In Figure 1 we demonstrate the interrelationships between 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, carbon, water, air and nutrients, etc., with important characteristics that we identify through soil formation processes such as horizonation, aggregation and colloid formation (Churchman, 2010). Soil stocks constitute 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 interaction with the wider environment. Ecosystem services result from the flows of materials and energy. These include outflows of carbon in food, feed, or fiber, inflows of carbon which aid climate regulation, the contribution of soils to water regulation and filtering, and waste disposal and recycling. Building or improving 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 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, whilst 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‘, whilst 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 over 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 counter-productive in discussion with policy makers, 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 policy makers and their generation, is an important challenge for soil science. Figure 1, shows that all 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 in order to combine these concepts into a useful framework. We identify four areas that require further research, development or synthesis to provide tools for bridging the science / policy divide:

1) Framework development
2) Quantifying the soil resource, stocks, fluxes, transformations and identifying indicators
3) Valuing the soil resource for its ecosystem services
4) Developing management strategies and decision support tools.

Framework Development: Daily et al. (1997) presented perhaps the first attempt to identify distinct soil ecosystem services (Table 1). 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 is 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) provide 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 Banzhof, 2007; Wallace, 2007), argue 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 which 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 soil natural capital, for instance conversion to intensive agriculture without some form of regeneration, a more extreme example being 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 under-emphasized 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) has 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.

Quantifying the soil resource, stocks, fluxes, transformations and identifying indicators: 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, since soil structural change may not be explained by a reductionist approach (de Jonge et al., 2009). Further, measuring the change of soil stocks through 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/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 change in the magnitude of the stock. This still requires a one-time estimate of stock to determine a baseline for natural capital. This approach is also not trivial as closing the mass balance is challenging, though 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 carbon fluxes from peatlands, and for looking 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), though there is still much discussion with regard to which are the most appropriate. 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 policy makers 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 carbon stocks and change for the Kyoto Protocol, or carbon footprinting for products (British Standards Institute, PAS 2050). In addition, we should consider an indicator framework that will allow us to assess the function of man-made or reclaimed soils. The challenge is then to use existing indicators of soil quality while shifting their focal point towards ecosystem services.

Valuation and tradeoffs: There will always be tradeoffs among ecosystem services, manufactured goods and other sources of human wellbeing. We implicitly ascribe relative values to them whenever we choose between alternative actions such as deciding whether to use land for production agriculture or a wildlife reserve. In order 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 wellbeing 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 GDP, which at present only incorporates goods and services traded in markets or supplied by governments, ignoring other sources of human wellbeing such as flood control and carbon sequestration which are incompletely valued by markets (OECD 2011).

In addition, GDP, which is a measure of the flow of goods and services, does not take into account the depreciation of natural capital/resource stocks. While some national accounting measures are estimated net of depreciation/degradation of manufactured capital, the depreciation/degradation of natural capital is generally ignored. Such externalities need to be internalized in order 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. GDP) has yet to be fully understood. This may pose a substantial challenge to approaches by which society currently makes decisions. 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 these decision tools need strong input from a soil management perspective, especially with regard to land-use. A prerequisite, and current research challenge, is to understand the interaction between 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 (SoE) reporting.

4) Engaging in the development of decision support tools that incorporate ‗soil change‘, that will enable the most informed comparison of trade-offs 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 et al., 2004; MEA, 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-wellbeing, the Earth‘s life support systems, and the diversity of life on this planet.

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

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 hydrological 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); the table does not provide an exhaustive list but acts as a guide for classification.

Natural capital	**Measurable or quantifiable soil stock**
1) MASS	
Solid	*Inorganic material I) Mineral stock and II) Nutrient stock*
	Organic material I) OM/Carbon stock and II) Organisms
Liquid	*Soil water content*
Gas	*Soil air*
2) ENERGY	
Thermal Energy	*Soil temperature*
Biomass Energy	*Soil biomass*
3) ORGANIZATION / ENTROPY	
Physicochemical Structure	*Soil physicochemical organization, soil structure*
Biotic Structure	*Biological population organization, food webs and biodiversity*
Spatiotemporal Structure	*Connectivity, patches and gradients*

Figure 1. Illustration of the temporal balance between soil natural capital and ecosystem goods and services supporting the concept of ‗soil change'. The inclined pale green arrow through soil natural capital indicates capital improvement, whereas the descending red arrow is capital degradation. In time, ecosystem services will diminish if capital is degraded; conversely, building capital may increase soil capacity to deliver goods and services. This is a broad generalization as building capital may also result in some disservices. The end goal is a sustainable balance of capital and ecosystem services.