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Review: Natural Capital and Ecosystem Services, Developing an Appropriate Soils Framework as a basis for Valuation.

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ABSTRACT

Natural capital and ecosystem service concepts are embodied in the ecosystems approach to sustainable development, which is a framework being consistently adopted by decision making bodies ranging from national governments to the United Nations. In the Millennium Ecosystem Assessment soils are given the vital role of a supporting service, but many of the other soil goods and services remain obscured. In this review we address this using and earth-system approach, highlighting the final goods and services soils produce, in a stock-fund, fund-service model of the pedosphere. We also argue that focusing on final goods and services will be counterproductive in the long run and emphasize that final goods and services are derived from an ecosystem supply chain that relies on ecological infrastructure. We propose that an appropriate ecosystems framework for soils should incorporate soil stocks (natural capital) showing their contribution to stock-flows and emergent fund-services as part of the supply chain. By so doing, an operational ecosystems concept for soils can draw on much more supporting data on soil stocks as demonstrated in a case study with soils data from England and Wales showing stocks, gaps in monitoring and drivers of change. Although the focus of this review is on soils, we believe the earth-system approach and principles of the ecosystem supply chain are widely applicable to the ecosystems approach and bring clarity in terms of where goods and services are derived from.

1. Introduction

Widespread concern about increasing pressures on the Earth's resources (Rockstrom et al., 2009) has led many governments to focus on consideration of environmental sustainability. Sustainable development is seen as desirable, though its proponents differ in their views of what is to be sustained, what is to be developed, how to link the environment and development, and over how long a time frame (Kates and Parris, 2003). However, there is widespread agreement that if it is to be achieved, ecosystems, and the benefits their good management brings, need to be better represented in decision-making tools and in indicators of progress (such as Gross Domestic Product, GDP): this is the ecosystem approach to sustainable development (Westman, 1977; Daily 1997). Monitoring and research in environmental fields, including soil science, need to adapt to the changing policy landscape brought about by this approach (Robinson et al., 2012).

In this paper we introduce the ecosystems approach in its broader context: ecosystem services and natural capital: and suggest how soil scientists should interpret them in the context of the earth-system. Moreover, we present a synthesis of ecological economics approaches with ecological and soil concepts in a natural capital, stock-flow, fund-service framework (Georgescu-Rogen 1971; Daly and Farley, 2011) pertinent to soils. The stock-flows are the tangible goods that move around the earth-system and are materially transformed into what they produce, and are a quantity. Fund-services are intangible, they do not become embodied in the thing produced, but are emergent functions that arise as something is produced, and as such they are measured in units of physical output per unit time. We next discuss what these concepts mean for monitoring and research in soil science, illustrating our points by presenting a synthesis of national-scale data (for England & Wales) and describing how it might be developed to respond to the demands of the ecosystems approach. Finally, we identify further challenges posed to soil science by the ecosystem approach, and the next steps which we suggest should be taken.

The ecosystems approach to sustainable development.

The ecosystems approach to sustainable development ("the ecosystems approach") has been promoted by many international organizations including: the Conference of the Parties to the Convention on Biological Diversity (CBD), the Food and Agriculture Organization of the United Nations (FAO), The Organisation for Economic Co-operation and Development, the United Nations Environment Programme, and the United Nations Development Programme. Moreover, countries such as the UK are adopting the ecosystems approach for national-level environmental policy development (Defra, 2011). The CBD defines the approach through 12 principles (Table 1). Two of the most important features of the approach are that it is inherently anthropocentric and focuses on decision-making. Thus, it recognises: the importance of managing ecosystems in a socio-economic context in order to maintain ecosystem services for humans and that conservation of resources must be balanced with their use (Principles 4, 5 & 10). Furthermore, it is argued that the power to choose the ends of ecosystem management (not necessarily the means) should rest with society, not scientists (Principle 1, also 11&12). Also of interest to soil scientists, is the recognition that change is inevitable (Principle 9).

1.1 Ecosystem services

The concept of ecosystem services, though prominent within the ecosystems approach, has proven even more influential on its own. Ecosystem services are the foundational concept of the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB) initiative and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES), the so-called IPCC of biodiversity (Marris, 2010); it is a concept that pervades all current discourse about the environment. The success of ecosystem services means they cannot be ignored by any scientist working on any part of the environment. However, creating an operational concept for research, monitoring and management is deeply problematic and challenging.

1.2 The fuzziness of ecosystem services

Definitions of ecosystem services have abounded, since the concept developed from papers such as Westman (1977). Fisher et al. (2009) provide a recent overview of how ecosystem services are defined, indicating that the literature has no commonly accepted consistent definition; the MEA (2005) definition is perhaps the most familiar: ”the benefits people obtain from ecosystems.” In public discourse at least, MEA (2005) has been most influential, yet several authors have criticised this rather loose definition. First, Boyd and Banzhaf (2007), then Fisher and Turner (2008) argue that a service is not the same as a benefit: that whereas ecosystem services are purely ecological phenomena, benefits are produced when ecosystem services are combined with other forms of capital (human, physical etc). Although Wallace (2007) and Boyd and Banzhaf (2007) believe that a single unified definition of ecosystem services is necessary to allow proper accounting, Fisher and Turner (2008) argue that different definitions may coexist for different purposes. The ongoing debate over what ecosystem services are, combined with the near ubiquity of the term, means that ecosystem services are a “fuzzy concept”: undoubtedly influential, but problematic as an analytical concept. However, the lack of general agreement creates scope for contributions from soil scientists to further develop the framework and ensure soil functions, vital to the maintenance of the earth-system and human wellbeing, are dealt with appropriately.

1.3 Natural Capital

The earliest reference to natural capital we found dates to 1837 (Badgley, 1837), and was more recently coined by Schumacher (1973), and used by Costanza and Daly, (1992) but really brought to prominence by Costanza et al., (1997). Costanza et al. (1997) define it as, “the stock of materials or information contained within an ecosystem”. Natural capital and stocks are of obvious relevance to soil science, given the widespread assessment of soil stocks through survey and inventory. However, references to ecosystem services have far outstripped those to natural capital (Table 2), and continue to grow more rapidly, while natural capital is not mentioned at all in the 12 principles of the ecosystems approach (Table 1); it is however, prominent in the UK government’s white paper on the environment (Defra, 2011). Perhaps surprisingly, natural capital appears to be particularly under-represented in the soils literature (Table 2). The greater focus on final ecosystem service delivery (relative to natural capital) raises the concern that the components of ecosystems such as biodiversity or soils might be overlooked if their link to final ecosystem services cannot be clearly demonstrated.

1.4 Ecosystem services, natural capital, and decision-making

The concepts of ecosystem services and natural capital have proved difficult to use in valuation, and decision-making (decision-making implies valuation, whether explicit or not). Although it is common to refer to the value of an ecosystem (i.e. natural capital) or its services, careful economic valuation rarely produces anything of the kind, for three reasons.

1. As Fisher and Turner (2008) point out, it is the benefits which impact directly on human welfare that are valued, and these are a combination of ecosystem services (or natural capital) and human or physical capital.
2. It is the change in the ecosystem service or natural capital which is valued, not the ecosystem service itself, and only at the smallest of scales will the two be identical. As

Toman (1998) has pointed out, any attempt to estimate the "total value of the world's ecosystem services and natural capital" (as per Costanza et al 1997) would be a "serious underestimate of infinity", and a similar criticism could be levelled at total valuations of a nation's ecosystem services.

3. Economic valuation is predominantly concerned with the effects on human welfare of specific and plausible human actions, which may affect ecosystems, the services they provide, or the way these services are used. It is really the human action or intervention which is valued, not the ecosystem or ecosystem services which it affects.

Since virtually all ecosystems of interest are already in some way shaped (and in many cases created) by human action, it is difficult to identify truly *natural* capital, or purely *ecological* services: is soil that has been farmed and maintained for centuries really *natural* capital? Is it worthwhile or even feasible to try to apportion 'credit' where it is due? There is a danger that the ecosystem services concept may obscure the intricate co-existence in most parts of the world between humans and their environment: that what ecosystem scientists are really studying are socio-ecological systems, undermining the holism called for in the ecosystems approach.

In summary, the concepts discussed above, particularly ecosystem services, have been extremely influential in both public and academic discourse about the environment, which is why soil science must engage in this debate and in the further development of concepts and frameworks. These concepts may have served to alert a wider audience to what environmental managers and soil scientists have known for a long time: that ecosystems, as human-environmental systems, can make an enormous contribution to human wellbeing if managed appropriately. In the next section we suggest how soil science can best respond to the challenges posed by this evolving paradigm in environmental management.

2. How should soil science respond to the ecosystems approach

2.1 Ecosystem services and natural capital in soil science

The ecosystems approach has gained more traction in the agricultural context than soil science *per-se*, probably because of the emphasis on final services like provisioning (Antle and Stoorvogel, 2006; Dale and Polasky, 2007; Swinton et al., 2007; Zhang et al., 2007; Power, 2010; Sandhu et al., 2010a; Stallman, 2011). In ongoing discussion of typologies and classifications for ecosystem services, soils tend to be viewed in the context of supporting above ground ecosystems, (De Groot et al., 2002, MEA, 2005) rather than for more specific goods and services that soils themselves provide. A lack of consistent typology, means that increasingly, properties, processes, functions, and services become used interchangeably, leading to confusion and making the development of a consistent valuation approach difficult. Daily et al. (1997) was perhaps the first to attempt to classify the ecosystem services provided by soils in their own right and this has been followed by other classifications (Wall et al., 2004; Andrews et al., 2004; Dominati et al., 2010), with many following the broad provisioning, regulating, cultural and supporting typology from the MEA (2005). Many of the articles have focused on promoting the importance of soil properties, processes and functions (Andrews et al., 2004; Haygarth and Ritz 2009; Powlson et al., 2011), whilst there is an increasing interest in the role of the below ground biota and microbial communities in providing services (Wall et al., 2004; Bell et al., 2005; Barrios, 2007; de Bello et al., 2010; Gianinazzi et al., 2010; Guimarães et al., 2010; Smukler et al., 2010; van Eekeren et al., 2010).

Soil natural capital, with its focus on stocks, is perhaps more intuitive to soil science as these are routinely measured and inventoried. Palm et al. (2007) defined soil natural capital as texture, mineralogy and soil organic matter. This was followed by a more in-depth definition involving 'matter, energy and organization' presented by Robinson et al., (2009). The concepts of natural capital and ecosystem services are sometimes seen as competing concepts but increasingly, especially with soils, they are seen as complimentary with the need for synthesis into a single soil-based framework (Dominati et al., 2010). The need for a consistent classification and framework within the ecosystems approach for soils is clear if valuation is to be conducted, and will bring the benefits of better identifying and defining the important soil stocks and services and communicating these to policy makers, especially in an increasingly regulatory environment (Bone et al., 2010). In addition, classification provides a language of communication, it helps us identify if things are missing, it will allow us to group new services with existing ones, provide a common reference for those already identified, and create better cross linkage with other ecosystem service to decision making frameworks.

2.2 Ecosystem service frameworks

Frameworks must incorporate soils so that society understands both the importance of soils, and that soils change on policy relevant time scales (Robinson et al., 2012). Soils are a dynamic system that continually evolves through soil formation and development and what may be termed anthropogenic soil change (Richter et al., 2011): mankind's intervention to adapt, adjust and manage soils for human benefit. Any framework must convey: to what extent change is inevitable, and how our interventions might accelerate or alter change.

One of the major drawbacks of the current ecosystem service framework with regard to soil is that it focuses on the flows of final goods and services and is biosphere centric. If our 'policy ends' are to better manage the earth-system, and its resources, we need to take an earth-system perspective and set soils and the pedosphere in this context. Currently in the MEA soils that contribute to final goods and service delivery are easily overlooked. This has caused either a lack of engagement with the soils community, or a response such as that of Lavelle et al.'s (2006), who stated, "Invertebrates play significant, but largely ignored, roles in the delivery of ecosystem services by soils at plot and landscape scales." An impediment for soil science is that soils provide limited flows of final goods: peat, topsoil, turf and minerals perhaps being the most easily identified, and as a result feature little in the ecosystem services framework and any subsequent valuation as a distinct entity; but they are fundamental in the delivery of many final services by which they are subsumed.

Dominati et al. (2010) recognized that a combined natural capital and ecosystem service approach is needed for soils. Focusing solely on final goods and services can lead to a problem analogous to that of using GDP as a welfare indicator: since GDP measures only flows, it tells one nothing of the sustainability of resource use, or what resource remains. Similarly, focusing only on final goods and services, tells little about the state of the ecosystem service delivery mechanisms. The recent UK National Ecosystem Assessment (NEA, 2011), presents a conceptual framework (NEA, Fig 2.2) that expands on the MEA (2005). The NEA framework has soil formation and primary production as a starting point on which processes act such as nutrient cycling, supporting the delivery of final ecosystem services, and then providing goods that are valued. This recent work develops the supporting services area which is essentially a black box in the MEA, and moves us closer to what might be considered an ecosystem service supply chain.

We maintain that it is vital that our overarching frameworks are holistic, embody an earth-system approach, and that soils in the form of the pedosphere are a fundamental component if the 'policy end' is to be improved earth-system management. We spend the rest of this section synthesizing soil and MEA concepts into the increasingly used ecological economic stock-flow and fund-service framework (Van Dyke, 2008; Daly and Farley, 2011, Farley and Costanza, 2010). The stock-flow and fund-service framework is particularly appealing because of its focus on earth-system management of scarce resources (Daly and Farley, 2011). This framework helps to differentiate between the tangible goods we obtain from ecosystems, and the intangible services, but also recognizes that ultimate classification as a good or service depends on use. In conventional economics the production of an output requires ‘factors of production’ which are the inputs. For instance in car manufacture this might include the raw materials, steel, plastic, wood, and rubber etc. as well as the assembly line, robots, presses and other machines. The raw materials are fundamentally transformed and used up in production, whereas the machines in the assembly line are basically unaltered by the process, just a little worn, but not fundamentally altered. So it is with ecosystems, according to the MEA (2005) there are provisioning goods that we harvest from ecosystems, such as food, feed and fibre; and regulating, cultural and supporting services, these clean, buffer, deliver, and filter but are not used up. In the stock-flow and fund-service framework the stocks result in flows of raw materials, some of which we harvest and are the structural components of an ecosystem, whilst processes act on multiple stocks within the ecosystem resulting in functions that are an emergent behaviour of the ecosystem resulting in fund-services. Taking an earth-system approach (Fig 1.), environmental scientists recognize the major compartments of the earth-system as spheres, the atmosphere; hydrosphere, including oceans, surface and ground water and lakes; the terrestrial biosphere with its plants and animals; the pedosphere, the thin skin of soil around the earth, and the geosphere, containing rocks and minerals. In addition, we identify an anthroposhere, recognizing we live in a coupled human-environment system.

Soils in the pedosphere are set in the context of the earth-system in Fig. 1. The building blocks of the pedosphere are soil natural capital stocks, which we can differentiate as abiotic and biotic in the brown box at the base of the figure. The natural capital framework of Robinson et al. (2009) is adapted to highlight the abiotic and biotic components of the soil ecosystem. Within the soil ecosystem the abiotic components provide the raw materials which are processed by the biotic component. Within the soil ecosystem there is constant flux of energy and materials and the reorganization and formation of new soil by physical, chemical and biological processes (S-F 3&4). The soil biota performs as the engine powering biogeochemical cycling in the earth system. This internal cycling creates outputs to the other spheres, hydro, bio and atmosphere of intermediate goods such as water, nutrients and gases (S-F 6) and is fuelled in part by outputs from other spheres in the earth-system in terms of wastes, exudates or weathering products for example (S-F 5).

Human intervention from the anthroposphere harvests goods from the environment. Soils are not often considered in terms of the harvested products they supply as final provisioning goods, but these should be recognized and include commodities of economic importance, such as topsoil, subsoil, turf grass and minerals (Fig.2). The US turf grass industry alone is considered to contribute more than $1 billion to the US economy annually (Christians, 2011). Soil biota is also harvested through extraction in the search for new biomedical resources. The soil ecosystem provides a vital, underappreciated, gene pool and biological resource from which many of our antibiotics have been derived (D'Costa et al., 2006). Methods of extracting, growing and reapplying soil biological crusts are also being investigated as a means of stabilizing soil surfaces to reduce dust emissions, something they have always done in the natural environment. Only a fraction of the soil biota has been explored, and many organisms remain to be discovered that can be of benefit to our existence in a known capacity.

All the processing and use of final and intermediate goods produces output/waste streams (S-F 2,4 and 5). Moreover, the anthroposphere produces manufactured inputs such as fertilizer and soil stabilizers. Although the movement of outputs is a stock-flow, the transformation of outputs is a fund-service, and one worth singling out. Soils are commonly used as the waste absorption repository for both anthropogenic derived outputs, and non-anthropogenic outputs. A vital aspect of this is the output/waste absorption capacity, as output transformation has a fixed upper level to its processing rate. The only way to alter the rate is to build up the natural capital and increase the quantity and functional biodiversity of organisms that process outputs; which adds to the argument for making natural capital and ecological infrastructure highly visible in frameworks. This is one of the often overlooked aspects of current agricultural systems where fertilizer substitutes soil derived nutrients for plants. This is the problem with short-term single use management, in this case increased production. Production increases obtained using fertilizers, pesticides and tillage reduced organic matter levels, reducing the soil natural capital stocks of carbon, and organisms that it supports, as a result the soils ability to absorb waste and assimilate it back into ecosystem becomes more limited. This is especially the case with nitrogen, where nitrogen pollution is common-place (Rockstrom et al., 2009).

The fund-services are shown above the stock-flows in Fig.1, a company class typology illustrates services commonly identified with the anthroposphere (F-S 7). These are the types of services commonly dealt with in national accounts as well as policy making. The environmental stock-flows result in a range of environmental fund-services (F-S 9,10 & 11). Both the internal and external stock-flows, involving the pedosphere (S-F 3-6), result in soil formation (F-S 9), termed supporting services in the MEA. In this earth-system approach to ecosystem services, ecosystem formation is an important fund-service, be it the diversity and complexity in a soil, forest, lake, marine or prairie ecosystem. Intermediate fund-services (F-S 10) are those with no recognized direct benefit to the anthroposphere, but are often important to the functioning of the ecosystem.

Soils contribute to a wide range of other emergent fund-services through interaction of the pedosphere with other compartments of the earth-system. Some of the more important ones are listed (Fig. 2). We now know that soils are a major store of global carbon and regulate GHG emissions, but we are also beginning to understand the important role of soil moisture as a buffer to extremes of heat and cold (Seneviratne et al., 2006). Both the strength and persistence of heatwaves in terms of loss of life, and cold spells, causing damage to infrastructure, especially by deeper frost penetration affecting pipe work; these have serious financial consequences for society. Given that the majority of our infrastructure is supported by, or surrounded by soil, slips, slides, and shrink swell affect costs, as does chemical weathering of concrete by the soil solution.

Soil biota contributes a major part to fund-services, soil is simply not soil without the biotic component. Biodiversity is recognized by some as a final ecosystem service in its own right (Eigenbrod et al. 2010). There is no doubt that whether as a final, supporting or intermediate service contributing to final services, soil biota and especially their functional diversity are a key component of the functioning of the earth-system. Barrios (2007) has explored this in great detail, identifying key functional groups that are involved with both intermediate and final services. He identifies 6 major functional groups which appear in the biotic compartment of the soil natural capital in fig. 1: the microsymbionts involved with nutrient uptake by plants; decomposers and elemental transformers involved with nutrient cycling; ecosystem engineers that modify soil structure sequestering carbon, enhancing aggregation, which affects hydrological and GHG regulation, dust emission etc; then there are the soil borne pests and diseases which result in disservices, but are regulated by the micro-regulators. By adopting this earth-system approach, soils, as well as all other compartments of the earth-system, play a much more visible role in the supply chain for ecosystem goods and services (Bristow et al., 2010; Jury et al., 2011). Thus this synthesized framework, in part, begins to address the role of soils in both and earth-system context and in terms of ecosystem goods and service delivery.

2.3 Decision-making and valuation for management

In this section we focus on ecosystem services in the context of decision making and tradeoffs rather than national accounts. Soil management for single functions can often be assessed based on empirical evidence and observed relationships, and attempts have been made to value or determine value systems for particular soil components (Decaens et al., 2006; Clothier et al., 2008; Rabotyagov, 2010; Sandhu et al., 2010b). However, optimising the multifunctional use of soils requires both models and monitoring in an integrated package that gives the best understanding of the response of the soil system within its ecosystem context, as well as a series of tools that can be used to assess tradeoffs for decision making. It is questionable whether such models currently exist: InVest (Nelson et al., 2009) and Polyscape (Pagella et al., 2011) are attempts to address this integrated modelling approach, but these are limited mostly to soil hydrological and carbon flux assessment for soils. Soil biodiversity and structural dynamics are not currently incorporated, and it remains extremely challenging to derive meaningful estimates of net-benefits for management decisions involving complex ecosystem service supply (Fig. 1). These models also focus on assessing ecosystem functions: combining them with economic assessment has yet to be done in any meaningful way. Cost benefit analysis (CBA), is often viewed with suspicion by those working with the environment, and yet there is much to learn from it as a framework which may help to systematically, and coherently identify the effects of a certain measure, using valuation as a means of making things comparable (Hansjurgens, 2004).

CBA allows us to compare alternative management actions. To do this we need to understand the dependence of final ecosystem service provision on ecological infrastructure (and how this is affected by human actions) by having a good understanding of the ecosystem service supply chain, its quality and health, and the consequences of adapting and modifying the supply chain. Perhaps a convenient way to do this is to model components and function of the ecosystem at an appropriate scale. This itself raises a challenge for soil science, to develop integrated soil system function models that describe ‘soil system behaviour’ for the provision of all services in the ecosystem context at a desired scale. We have detailed water, gas and heat flow models (Simunek et al., 2008), and nutrient cycling models (Johnson et al., 2000), but these tend to be stand-alone and are not linked to biodiversity or ecosystem models, and moreover not linked to management. A suite of soil science models are needed that are able to predict the effects of specific management actions on soil functioning (Cichota and Snow, 2009). Thus they don’t just need to describe how soils currently function, but how that changes if we do something. In order to understand ecosystem service provision it might be time to step back, and instead of making models more detailed, make general models more holistic. These models should recognize the important soil stocks and infrastructure in the ecosystem service supply chain. Soil science and those who manage soils for provisioning and regulating services intuitively understand the importance of soil infrastructure, which is why many monitoring programs measure soil stocks as indicators of soil performance (Emmett et al., 2010).

3. Monitoring and measurement

3.1 Soil state and change

One risk in focusing too much on final ecosystem services is that the stocks and intermediate services that are responsible for final delivery may be overlooked (Fig. 1). This is detrimental if stocks decline unnoticed in support of final ecosystem goods and service delivery, e.g. nutrient stripping in crop production, leading to a positive feedback with declining final services. There are two further reasons that stocks are important for monitoring the state-and-change of soils (Emmett et al., 2010). First because flows can be inferred from stocks but stocks cannot be inferred from flows without a baseline assessment of stocks. The counter argument, often in the context of carbon emissions, is that it is the flux in or out of soils that matters, i.e. determining if they are a source or sink. However, it is only through a stock assessment that we can determine the magnitude, of for instance, the soil carbon pool, and whether it is likely to continue to be a significant source of GHG if not managed properly. Knowing the size of the available nutrient stock in soils is also of strategic value. In the case of peak phosphorus (Clabby, 2010), it is important to know soil reserves, the rate at which these will be released into the available soil solution pool, and the amount removed and returned during crop production if we are to plan for a sustainable future. In the same way, knowing the stock of soil moisture is of value to a farmer in determining when to irrigate. Any monitoring scheme will always be more powerful if both stock and flux are determined and used to cross check with each other in the assessment of change (Richter et al., 2007).

The second argument for focusing on soil stocks is to ensure continuity with historical data which, for soils, has tended to focus on soil stocks. In the United Kingdom LandIS, the land information system run by the National Soil Resources Institute (NSRI), a centre within Cranfield University, G-BASE (Simpson et al., 1996) from the British Geological Survey and Countryside Survey (Emmett et al., 2010) from the Centre for Ecology and Hydrology all have data that goes back decades, which if we stopped monitoring stocks would be almost redundant for this purpose. This wealth of data may help us to determine how soils have changed over time, especially following anthropogenic activity. Focusing simply on MEA final ecosystem goods and services can overlook this resource. Concurrently, soil monitoring needs to assess if it is fully capturing soil change, not just current state. We need to re-evaluate our monitoring in the light of the ecosystem approach: are we measuring the things which matter? Will our monitoring inform management for society's objectives? The soil natural capital framework (Fig. 1) (Robinson et al., 2009) provides an opportunity to determine which stocks are currently being monitored and which are not. Knowing these variables is of value in assessing soil performance. In the following section we present a case study for England and Wales identifying data sets that contribute to soil stock state-and-change monitoring, which could form the basis of a national soil natural capital assessment.

3.2 Exemplar datasets for assessing natural capital in England and Wales

To illustrate the importance of both soil natural capital and ecosystem services in an ecosystems approach, we assess the current state of soil monitoring for England and Wales, countries adopting a national ecosystem approach (Defra, 2011).

Society, through EU, UK and Welsh Government policy and regulation increasingly intervenes in land management with regard to balancing a range of pressures from food production to climate change (Haygarth and Ritz 2009), in line with an ecosystem approach. In order to develop effective monitoring and assessment appropriate to answering questions derived from an ecosystems approach, we must have appropriate frameworks in place to allow valuation for decision-making, and feed the desired valuation results back. No agreed framework exists to date, and so this section identifies the steps and relevant information required to attain an appropriate ecosystem approach for soils.

Robinson et al (2012) identified four key research areas needing attention for communicating soils research effectively in an ecosystems context:

1) Framework development, one that gives a balanced emphasis to stocks and flows.
2) Quantifying changes to the soil resource. This can be achieved through monitoring and modelling of stocks, fluxes, and transformations, and identifying appropriate indicators that can be used in monitoring schemes to tie modelling to reality.
3) Valuing the net benefits to society from alternative soil management options.
4) Developing management strategies and decision-support tools.

A brief review of soil survey in England and Wales shows that most of the information held describes soil stocks, and as stated previously to focus solely on final services and ignore this wealth of stock information would be detrimental. Therefore, any framework should achieve a balanced recognition of stocks and services. Secondly, scale is an important consideration within an ecosystems approach (Hein et al., 2006). Decisions are made for different scales and Defra (2007) has identified: local (local government), regional (government offices) and national (England or Wales) scales as being important to their decision making. For most land managers we can add the farm scale to this also; whilst the ultimate aim may be to have scales of tens of meters helping individual householders and companies. Soil stocks alter in both space and time, and it is likely that stocks may contribute differently to soil function at different scales, this may have implications for valuation. For the purposes of this synthesis we focus on national and regional scales and consider soil stocks appropriate for these scales.

The soil resource: Defra identified the following soil functions as being of major national importance: 1) food and fibre production, 2) environmental interaction, 3) biodiversity and habitat, 4) protection of cultural heritage, 5) platform for construction, and 6) raw materials (Defra, 2009) (Table 3). Sustaining these functions is an important aspect of soil management. Maintaining and enhancing soil function requires policy developed from the best understanding of soil stocks, the services they deliver and soil behaviour, this requires spatio-temporal mapping and modelling of soils, within the correct ecological, hydrological, geological and landuse context that includes static and dynamic soil stocks.

Soil resources have been quantified for England and Wales by a number of soil inventories for different purposes which include, the (i) NSRI, LandIS database linked to the National Soil Map (NATMAP), which for England and Wales is based on soils found at 5691 points on a 5-km grid, (ii) NSRI resampling survey, (iii) Countryside Survey (CS), (iv) Representative Soil Sampling Survey (RSSS); (v) the Environmental Change Network (ECN), and (vi) Biosoil. Table 3a-c synthesizes data from these surveys into the matter, energy, and organisation natural capital framework (Fig. 1), then links them to the soil functions identified above and identifies drivers of change. The tables (3a-c) indicate that there is a lot of potential information available that fits well into a soil stocks framework. Classifying the available data according to the natural capital typology also allows us to identify gaps in monitoring; these include lack of more dynamic data such as soil moisture data which relates to understanding fund-services such as flood and drought potential, and heat-wave persistence and intensity (Seneviratne et al., 2006). Micronutrients represent another gap relating to food and fibre production and ecosystem health. Data is beginning to emerge on soil organisms but this is still in its infancy and remains a gaping hole in monitoring. Quantity and diversity results are available (Emmett et al., 2010) which underpin many functions, and the provisioning of biomedical resources; this is certainly an area where more work is needed, especially functional diversity and capacity, and linking these resources to valuation. No survey of soil gases is currently undertaken, this is primarily constrained by technology. Oxygen levels are important for plant growth (Letey, 1985), whilst carbon dioxide, methane and nitrous oxide are all important for understanding climate change. Measuring gases *in-situ* is difficult, though methods are becoming available (Turcu et al., 2005), whilst measuring fluxes is feasible but expensive using eddy flux towers, e.g. the American Ameriflux network (Falge et al., 2001). The structural components of soils, macroporosity, aggregation and connectivity are more difficult to assess: LandIS gives some assessment of the connection of soils with the landscape in the form of mapping units which are based on expert opinion and are unsatisfactory for determining change; moreover structure and its change at the scale of the pedon, for example, pores, peds and aggregate information is not available. Maintaining the aggregate stock has important impacts on final services such as carbon storage, flood regulation, and food provisioning for example.

Capturing and understanding 'soil change' is an important component of understanding how final ecosystem service provision affects the soil infrastructure and stock levels for sustainable soil ecosystem service provision. We also need to understand how to differentiate between how different drivers of change impact the soil final good and service supply chain and ultimately affect benefits and value. This is where Fig. 1 helps to begin to locate where drivers of change might impact along the supply chain. Countryside Survey was designed to assess state and change of above and below ground ecosystems (Smart et al., 2003; Black et al., 2003; Griffiths et al., 2011), whilst attempts have also been made to understand change by resampling the original soil survey data (Bellamy et al., 2005; Kirk et al., 2010). Assessment of change is increasingly important for determining how interventions impact, both at local and regional scales and underpins valuation. This may require regional monitoring, and monitoring of specific interventions to differentiate between large scale drivers of soil change and soil change due to intervention at local scales.

Soil, as seen from fig. 2, produces its own final goods and makes major contributions to the delivery of many final ecosystem fund-services. However, the important question is how do we recognize the role of soil in this delivery? The first step, presented here is recognizing the importance of all earth-system compartments in the delivery of final goods and services, not just focusing on the biosphere. We need to understand how changes in soil management for example affect these final fund-services. Another important question is: how sustainable is the supply chain for continued fund-service delivery, are we managing the stocks from which they are generated appropriately? This is where the combined stock-flow, fund-service model helps. Data is required that shows the stock and change over a suitable period of time, and links both flows and fund-services back to changes in stock in all compartments of the earth-system, which is why tables 3a-c are important in determining what stocks we monitor. We therefore propose that fig. 1 using an earth-system approach provides a more complete basis for identifying the contribution of soil ecosystems to ecosystem services, and provides a template for valuation advancing some of the concepts proposed in Dominati et al. (2010).

4. Future steps

Given the discourse in section 3, the soils community must build consensus to refine and promote a common soil natural capital / ecosystem service framework, such as the earth-system stock-flow, fund-service approach proposed here (Fig. 1). Appropriate bodies for addressing this might be professional societies or the newly formed Global Soil Partnership (GSP) supported by FAO, with the aim of developing an inter-governmental panel on soil (IPS) (FAO, 2011). The advances required with the ecosystems approach complement the five main pillars of action proposed by the GSP (Table 4).

In addition to the four scientific challenge areas outlined in Robinson et al., (2012) for soils, much scientific and economic evidence is unsuited to improving decision-making about ecosystem management. To do this, we need to estimate the costs and benefits resulting from a change in management. This means understanding the incremental effects of that change, especially on ecological infrastructure and supply chains, on ecosystems and on society. Because it would be prohibitively expensive to carry out scientific and economic studies for every decision, we need to be able to efficiently apply the results of past studies to new problems, a process known as benefits transfer in economic valuation. Yet this process is often hampered in several ways as detailed in the following paragraphs.

First, natural science research and monitoring is frequently directed towards testing hypotheses about how ecosystems function, rather than predicting the effects of specific changes in management, and the evidence base for many management decisions is often surprisingly weak, even in apparently well-studied systems. Monitoring of soil characteristics over time is of little use if changes cannot be related to their causal factors. The strong focus on statistical significance, as opposed to the shape of “dose-response” functions, in many natural science fields, often makes it difficult to interpret research in an applied setting.

Second, published studies, in the natural and social sciences, usually present only summary results, which are rarely sufficient to allow re-analysis for application to a new context, and the needs for ecosystem service analysis can be quite data intensive. Requirements for data archiving vary between journals, organisations and disciplines. Government organisations often fulfil an important and underappreciated role in archiving data as a component of their national capability and new journals focusing on environmental data sets are an important contribution to sustaining collective memory. Facilitating data access is an important step toward integrated ecosystem service modelling and evaluation.

For soil science, the challenge is clear: the development of a clear, operational framework to convey soils research within the ecosystems approach, but that also shows how soils interlink with the atmosphere, biosphere, hydrosphere and geosphere in supplying emergent fund-services, something we feel this paper contributes towards, so that soil science can advance toward valuation of soil goods and services, fully communicating the vital role of soils in sustaining the coupled human-earth system.

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Table 1. CBD Principles of the Ecosystem Approach (abridged from CBD http://www.cbd.int/ecosystem/principles.shtml)

CBD Principles of the Ecosystem Approach
1. The objectives of management of land, water and living resources are a matter of societal choices.
2. Management should be decentralised to the lowest appropriate level.
3. Ecosystem managers should consider the effects of their activities on adjacent and other ecosystems.
4. There is usually a need to understand and manage the ecosystem in an economic context.
5. Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority.
6. Ecosystems must be managed within the limits of their functioning.
7. The ecosystem approach should be undertaken at the appropriate spatial and temporal scales.
8. Management should be set for the long term.
9. Management must recognise that change is inevitable.
10. The ecosystem approach should seek the appropriate balance between conservation and use.
11. The ecosystem approach should consider all forms of relevant information, including scientific and indigenous.
12. The ecosystem approach should involve all relevant sectors of society and scientific disciplines.

Table 2 Articles or web pages referring to either ecosystem services or natural capital. Note: wild card characters were used to search for plurals.

	"ecosystem services"	**"natural capital"**	**Ratio ecosystem services: natural capital**
Google	1,190,000	493,000	2.4
Google Scholar	55,800	35,800	1.6
Web of Knowledge	3,338	659	5:1
Web of Knowledge with "AND soil*" as an additional qualifier	793	56	14:1

Table 3a. Soil mass stocks and potential soil data sets that might contribute to baseline stock assessment. Major data sources include (i) the land information system (LandIS); the National Soil Map (NATMAP); NSI resampling survey (NSI); Countryside survey (CS); Representative Soil Sampling Survey (RSSS); the Environmental Change Network (ECN), and the forest soil monitoring (Biosoil). Defra Soil functions: 1) Food and fiber production, 2) Environmental interaction, 3) Biodiversity and habitat, 4) Protection of cultural heritage, 5) Platform for construction, 6) Raw material.

Soil Stocks	Drivers of Change	Data Sources	Comments
Matter – solid **Inorganic material** **Mineral stock** Texture / mineralogy / soil depth / volume / mass / Link to soil functions: 1,2,3,4,5,6	*Long time scale* – Weathering, bed rock lowering. *Short-medium-long time scale* - Erosion through wind, precipitation or cultivation. Engineering and construction.	*Quantity*: *Soil texture*: LandIS has original data. BGS has high resolution PSD data for East Midland region of England using G-BASE. *Soil depth:* No systematic map of total soil / regolith depth is available for the UK. LandIS stops at ~1.2m. ECN will re-survey changes in soil horizon depths but only 12 sites nationally. BIOSOIL examines horizons of organic and mineral soils to a depth of 80cm. *Quality*: *Soil mineralogy*: BGS has basic mineralogy data held in Soil Parent Material Map database. However, it is geology based rather than measured soil data.	*Soil texture*: Is likely to be a reasonably static or very slowly changing dynamic variable. It could be substantially more spatially variable than LandIS sampling resolution. Landuse change may affect soil depth the most, particularly if soil becomes more susceptible to erosion. There is relatively little information on soil production rates. There is no current erosion map of Eng. & Wales, although Defra has undertaken monitoring programs in the past. Obtaining soil depth information may help with stock assessment. *Mineralogy*: Very little information on rates of mineral weathering and natural fertility replacement for Eng. & Wales. Skolkloster classes designed to assess mineral soils short term acid buffering capacity have been used to identify and map soils sensitive to acidification.
Matter – solid **Inorganic material** **Nutrient stock** Link to soil functions: 1,2,3,6	Nutrient mining from crop production, loss of topsoil from erosion, leaching, change of vegetation.	*Quantity*: LandIS contains K and P, extractable K measured through RSSS scheme for agricultural land. CS monitors soil P and mineral N. Biosoil monitors N as well as Ca, Mg, K, H, & Al.	Link between nutrient source areas, mineral weathering rates and soil nutrient stocks not well established. Monitoring of soil micronutrients is sparse.
Matter – solid **Organic material** **Organic Carbon** Link to soil functions: 1,2,3,6	Landuse change, especially vegetation or cultivation practice. Possible climate change response via bacterial Q_{10} relationships. Water logging (increase), aeration (decrease).	*Quantity*: Both LandIS and the CS have undertaken the resampling of SOC. Biosoil monitors forest soil C. *Quality*: It is yet to be determined how to assess this, studies on fractions may help.	NSRI indicated soil carbon stocks were decreasing, CS couldn't confirm this.
Matter – solid **Organic material** **Organisms** Link to soil functions: 1,2,3,6	Pollution, landuse change, especially vegetation and cultivation practice, soil physico-chemical properties, climate change.	*Quantity*: CS records state and change of selected broad invertebrate taxa and more specifically mites, springtails and collembolan.	Initial research suggests that soil microbial population spatial distribution may be correlated with soil pH. Maps of soil organisms have not generally been developed.
Matter – Soil liquid **Soil water content** Link to soil functions: 1,2,3,4,5	Climate change, land use and management change.	*Quantity*: LandIS has information relating to soil series soil water content at different suctions in its inventory. *Quality*: CS contains data for soil pH and its change. Some information on redox status can be determined from gleys in the LandIS data.	Soil moisture is the pool of water for life, it is an important environmental moderator by controlling soil microbial activity, gas content and redox.
Matter – Soil gas **Soil gas content** Link to soil functions: 1,2,3,4	Compaction changes in bulk density, changes in moisture regime.	*Quantity*: No survey of soil gas composition undertaken. CS has information on bulk density from which porosity is determined. NSRI have bulk density values for soil series and horizons in LandIS *Quality*: assessment of individual gasses, such as O_2, CO_2, CH_4 and NOx is difficult but new sensor technologies may help.	Oxygen is required for plant growth. Soils form an important buffer for climate regulation and are a big sink/potential source for greenhouse gases.

Table 3b. Soil energy stocks and potential soil data sets that might contribute to baseline stock assessment.

Soil Stocks	Drivers of Change	Surveys	Comments
Thermal Energy **Soil temperature** Link to soil functions: 1,2,3,4	Climate change, changes in moisture regime from drainage/wetting.	*Quantity*: The Met Office monitors soil temperature at some of its weather station network. ECN sites also include soil temperature monitoring.	Will be one of the major changes with climate change. The MET office has soil temperature maps (0-30cm) averaged over 30 years for each month and season.
Biomass energy **Organic carbon** Link to soil functions: 1,2,3,4	Landuse change, cultivation practice, clay content. Possible climate change response via bacterial Q_{10} relationships	*Quantity*: Both NSRI and the CS have undertaken the resampling of SOC. Biosoil monitors forest soil C. *Quality*: It is yet to be determined how to assess this.	NSRI indicated soil carbon stocks were decreasing, CS couldn't confirm this.

Table 3c. Soil organization / spatio-temporal structure of stocks and potential soil data sets that might contribute to baseline organization assessment.

Soil Stocks	Drivers of Change	Surveys	Comments
Physicochemical structure Aggregation / soil structure Link to soil functions: 1,2,3,5	Change in carbon status, organism dynamics, or wetting and drying regime. Management and trafficking. In coastal and high pH areas, sodium %.	LandIS would include this information at the time of sampling.	Soil structure is difficult to quantify, aggregate stability may be one direct method, determining the water release characteristic may provide an indirect method.
Biotic structure Biological diversity, food web structure and community organization Link to soil functions: 1,2,3	Pollution, landuse change / management, wetting and drying climate change,	The CS monitors soil invertebrates and makes measures of biodiversity. Information of foodweb structure may develop this area.	Reports results according to Broad Habitat, aggregate vegetation class and soil organic matter
Spatial-temporal Structure Landscape metrics Link to soil functions: 1,2,3,5	Erosion, construction	LandIS contains soil boundary information based on surveyor interpretation.	We have little understanding of how linear features, ranging from hedgerows to roads, impact soil biological function and movement and flow of mass and energy through the landscape.

Table 4. The Global Soil Partnership has proposed focusing on five main pillars of action to achieve its objectives (FAO, 2011)

PILLARS OF THE GLOBAL SOIL PARTNERSHIP
1. Harmonizing and establishing guidelines and standards of methods, measurements and indicators 2. Strengthening of soil data and information: data collection, validation, reporting, monitoring and integration of data with other disciplines 3. Promoting targeted soil research and development focusing on identified gaps and priorities and synergies with related productive, environmental and social development actions 4. Promoting sustainable management of soil resources and improved global governance for soil protection and sustainable productivity 5. Encouraging investment and technical cooperation in soils

Figure 1. The coupled human-environment system; with solar radiation and heat from the earth's core powering the system. Stocks flow from the environment to the anthroposphere when harvested (S-F 1&2); internally between abiotic and biotic pools shown here for the pedosphere (S-F 3&4), and across boundaries between earth system compartments, with the outer boundary of the pedosphere illustrated by S-F 5&6. Stock-flows are tangible, representing stocks which are the natural capital, and the flows of this capital that can be internal or external to a sphere. Fund-services are the intangible emergent services that result from stock-flow processes, in the human sphere (7) these may range from water regulation by dams and weirs to cultural services such as gardens. Each environment sphere provides a supporting service of ecosystem formation (9), in this case soil formation and a range of final regulating and cultural ecosystem services of human benefit (11). Intermediate services (8&10) are also generated, but as yet are not recognized as providing direct benefits to human welfare. The stock-flows represent the ecological or earth system infrastructure, which in combination with the resulting fund-services form an ecosystem service supply chain.

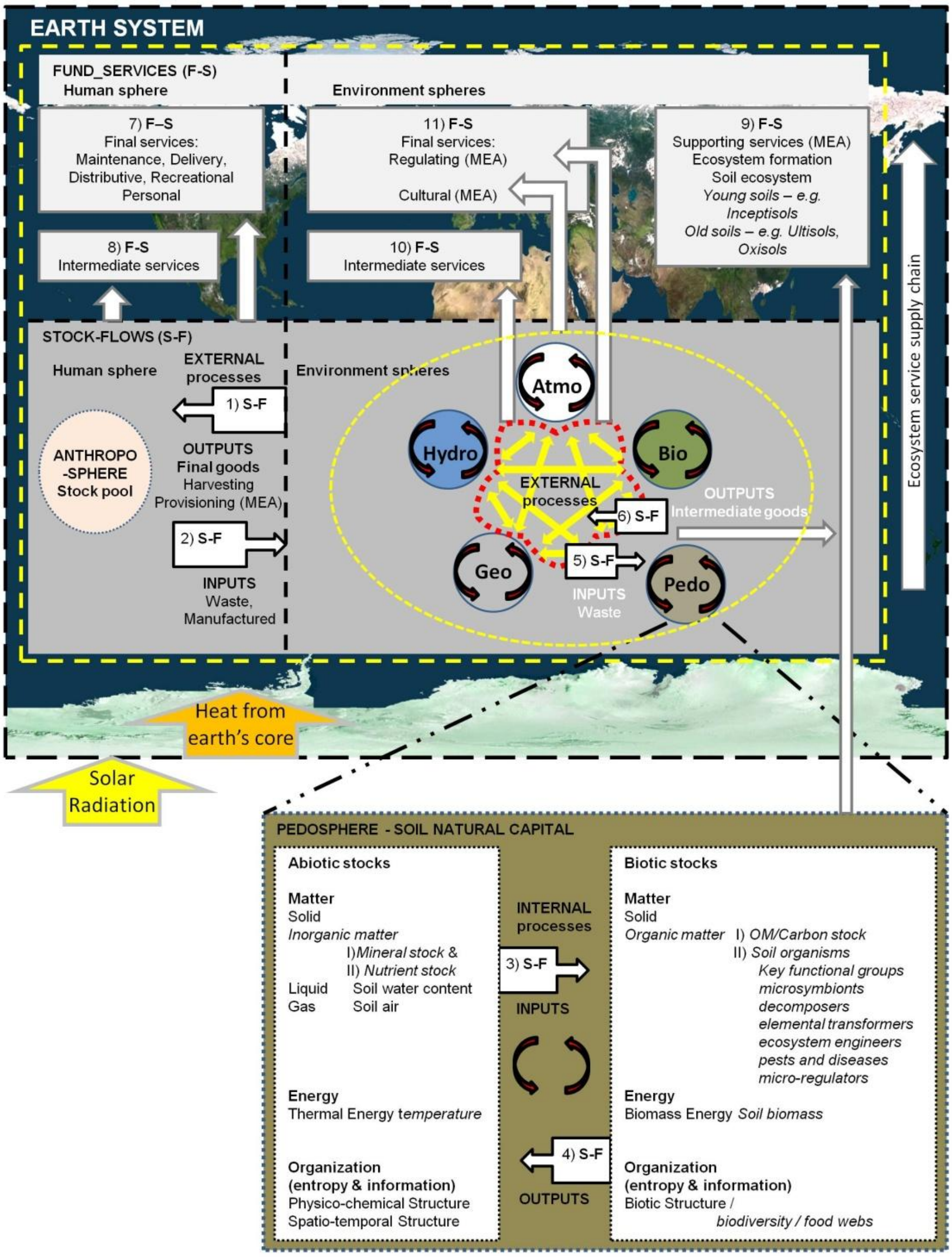

Figure 2. A more detailed view of the stock-flows and fund-services derived from the pedosphere and linked to the MEA (2005) typology; the numbers link to the compartments in fig.1. Waste processing services are an important fund-service and occur at all scales, it is worth remembering that they operate at a fixed rate with a fixed absorption capacity and are highlighted below.

1) Stock - Flow

Provisioning goods (MEA)
Topsoil
Peat
Turf
Sand / clay minerals
Biomedical Resources
Bio-resources, soil stabilizers, biological crust

11) Fund – Service

Regulating services (MEA)
Climate regulation
Buffering extremes of cold or heat
GHG regulation
Hydrological regulation
Buffering floods and droughts
Water filtration
Hazard regulation
Structural support buffering, shrink/swell
Landslides / slumps
Liquifaction
Dust emissions
Disease Regulation
Human pathogens
Disease transmission & vector control
Biodiversity
Gene pool
Pathogens

Waste processing services
Cleaning, degradation, transformation

Cultural services (MEA)
Sports field recreational surfaces
Preservation of historic artifacts
Landscape aesthetics
Burial grounds

9) Fund – Service

Supporting (MEA)
Soil formation and genesis