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Advances in Soil Ecosystem Services: Concepts, Models and Applications for Earth System Life Support

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Abstract

The ecosystem services approach is gaining wide acceptance at the policy making level as a framework for integrating science and policy regarding the natural environment. It is important that soil science clearly articulates how knowledge and understanding of the soils of the vadose zone can be transmitted through this framework into the decision making process. Competition between food production, living space, and maintaining habitat for all of earth's life forms has never been so intense, so the need for soil security and vadose zone protection is paramount. Soil management can no longer be thought of in terms of single function management, but needs to be considered and managed in the context of the multiple functions it offers. In this 10th anniversary issue of the journal we assess progress in the development of a coherent soil ecosystem services framework using the natural resource management stock-flow and fund-service resource approach. We go on to examine some of the areas where the application of an ecosystems approach is gaining traction; these include, national and local decision making, as well as support for legal arguments in court.

Introduction and Concepts

The Millennium Ecosystem Assessment (MEA, 2005) had a huge impact on the global environmental political agenda. It highlighted the extent of the decline of the world's ecosystems, and argued the vital importance of ecosystems for earth-system life support and human wellbeing. The Millennium Ecosystem Assessment was also heralded as a framework that bridged the science/policy divide, a framework that was capable of translating our best science, and processing that understanding into a cogent policy-relevant format using the value of ecosystem services. There are those who question what the ecosystem services approach delivers, (McCauley, 2006). However, it is beyond question that 'ecosystem service' concepts are shaping and impacting policy development and its implementation at the highest levels. The ecosystem services approach to sustainable development 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 (OECD), the United Nations Environment Programme (UNEP), and the United Nations Development Programme (UNDP). Moreover, governments of countries such as the United Kingdom are adopting an ecosystem services approach for national-level environmental policy development. Thus, as the science communities of hydrology and soils we cannot ignore this framework if we are to address wider stakeholder needs.

With it, the ecosystems approach (CBD, 2013) brings new terminology, Nature's stocks are termed 'natural capital', and functions from which we derive benefit are called 'ecosystem services'. These give our thinking about nature a more economic and policy relevant feel. The definition of ecosystem services has transitioned from being, "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life" (Daily, 1997) to being "the benefits people obtain from ecosystems" (MEA, 2005). Central to the ecosystem services approach is the attempt to value the benefits we obtain from nature. Costanza et al. (1997a) generated huge interest by first attempting to determine the annual value of nature's services at US$33 trillion. This was controversial and attracted criticism, with Toman (1998) pointing out that any attempt to estimate the "total value of the world's ecosystem services and natural capital" (as per Costanza et al. 1997a) would be a "serious underestimate of infinity." Similar criticisms could be levelled at total valuations of a nations ecosystem services. Despite these criticisms, economic valuation is being developed in different forms for a range of purposes, including for national accounts and for decision making tools for land management. This is because economic valuation is one way of comparing the options policy makers need choose from.

Ecosystem service concepts have also drawn opposition in the national press in the United Kingdom (Monbiot, 2012). In his article, Monbiot writes of concern about the privatization and commodification of nature. But as Costanza et al (2012) argue, ‘the valuation of natural capital and ecosystem services, including in monetary units, is not (or should not be) a prelude to privatization.’ They added that, ‘many natural capital assets are, and should remain, common property and should be managed as public goods.’ Costanza et al. (2012) went on to argue that although people fear valuing ecosystem services, because this could expose nature to unfair appropriation by capitalism, economic valuation already occurs. The products we buy and benefit from, are derived in some way from harvesting nature. Ecosystems provide a myriad of benefits for societies, many of these benefits are not captured in the market system, so the true extent of the contribution of our water, air, soils and biological resources to socio-economic systems is often undervalued and thus neglected. Trying to capture all the facets of ecosystems and earth system resources into a conceptual framework that can be ultimately developed into an operational model for ecosystem management is therefore the focus of much research.

Growth of Ecosystem Service Concepts

The history of ecosystem service concepts can be traced back to 19th and 20th century thinkers and perhaps even further (Mooney and Ehrlich, 1997). However, the paper of Westman (1977) stands out as a defining contribution in terms of the idea that ecosystems provide functions which are of societal value. It was not until the controversial paper of Costanza et al. (1997a) and books by Daily (1997) and Costanza et al. (1997b), that the concept began to gain traction. Since then, academics have seized hold of the concept and moulded and shaped it into a way to bridge the science-policy divide. The extent and rapidity of the uptake of the concept in academia is demonstrated by the exponential increase in the use of the ecosystem services terminology in the literature (Fig 1) (Dick et al. 2011). The colossal achievement of the Millennium Ecosystem Assessment cemented the ideas of linking ecosystems with human wellbeing (MEA, 2005). Since the initiatives such as the Ecosystem Service Partnership have developed and continue to refine this framework.

An ecosystem services approach offers a move towards sustainable ecosystem management across our society and economy via the use of financial incentives for responsible land and habitat management. This type of approach is not new. Many soil scientists will recognize these aims and approaches, as for example in the United States' 'Conservation Reserve Program'. In this program, the US Federal government annually 'rents' about 140,000km^2 of land to reduce soil erosion, improve water quality, enhance water supply through groundwater recharge, increase wildlife habitat, and reduce damage caused by floods and other natural disasters. This is achieved by payment of some US$1.8 billion of tax payers' money annually to farmers and landowners for planting long-term ground covers.

Conceptual Frameworks for Earths Resources

Different schools of thought exist concerning the application of ecosystem services concepts. There are those who see ecosystem services as a good potential vehicle for nature conservation (Tallis et al., 2008), whilst there are those who are strongly opposed to using such an approach (McCauley, 2006). Nature protection through economic valuation is easily reversible when market conditions change; and the extent of nature protected using ES arguments has been tiny compared to that protected through legal conventions. These conventions can be diluted and weakened by the adoption of an economic approach. Others see the concept more as a management framework for the earth's resources (Daly and Farley, 2011). While ecosystem services is loved by some and hated by others, the question is whether it is useful as a conceptual framework. The authors think it is, especially with regard to thinking about soils in the context of resource use and the variety of benefits that society obtains from soils and the vadose zone.

The Millennium Ecosystem Assessment classified ecosystem goods and services into four categories: (1) Provisioning Services, the products obtained from ecosystems; (2) Regulating Services, the regulation of ecosystem processes; (3) Cultural Services, those obtained from ecosystems through spiritual enrichment, heritage, cognitive development, reflection, recreation, and aesthetic experiences; and (4) Supporting Services, those that are necessary for the production of the three other types of ecosystem services. This classification has been adopted widely, but with some modification, as for example the Common

International Classification of Ecosystem Services (CICES). The Economics of Ecosystems and Biodiversity study (Haines-Young, 2012), was realised under the UNEP umbrella and removed supporting services, arguing that society gains no direct benefit from supporting services. Another refinement used in the UK's national ecosystem assessment was the distinction between 'final' and 'intermediate' goods and services (NEA, 2011). Final services are those from which we draw direct benefit, whereas the intermediate services essentially support the others. The focus on final goods and services has lead some researchers to point out the importance of the supply chain (Mooney, 2010; Robinson et al., 2012), which final services can over look.

Soil Natural Capital

The first use of the term natural capital can be found to date back to the 1830's (Robinson et al. 2012). More recently, Costanza et al. (1997a) defined natural capital as, "the stock of materials or information contained within an ecosystem". Essentially the term natural capital is, 'an economic metaphor for the limited stocks of physical and biological resources found on earth' (MEA, 2005). Natural capital for us here is the tangible stocks; what can be seen, tasted, felt, heard, or smelled. Our discussion is of obvious relevance to soil science, given the widespread assessment of soil stocks through soil survey. Robinson et al. (2009) presented a first typology of soil natural capital based on matter, energy and organization, which has developed into a description that now recognizes the abiotic and biotic components independently (Figure 2). This is something that is important for recognizing the material transfers between them, which is what we would think of as soil formation. Dominati et al., (2010) proposed a complementary framework for soil natural capital putting the emphasis on the difference between highly dynamic stocks, e.g. soil properties, which are impacted by natural or anthropogenic drivers (e.g. climate or land use) in short time frames, and therefore manageable; and less dynamic stocks, the inherent soil properties, which are more difficult to alter.

Soil Ecosystem Services

Ecosystem services were defined by the MEA (2005) as, 'the benefits people obtain from ecosystems'. More recent definitions include, 'ecosystem services are the final contributions that ecosystems make to human well-being' (Haines-Young and Potschin, 2010). With regard to soils, Daily et al. (1997) were the first to identify distinct soil ecosystem services in a typology, which has been expanded on by others (Wall, 2004; Andrews et al., 2004; Clothier et al., 2008; Dominati et al., 2010); particularly in regard to the biotic components of soil (Barrios, 2007; Lavelle et al., 2006). Services are, by their very nature, intangible, i.e. they cannot be touched, gripped, handled, looked at, smelled, tasted or heard. They are the emergent result of the interactions/processes between stocks. With regard to soils, Robinson et al. (2012) compiled a list of the major goods and services from which individuals, or society, benefits (Table 1).

Ecological Infrastructure

The term 'ecological infrastructure' was introduced and elaborated in government policy reports in 1977 and 1981 in the Netherlands (Van Selm, 1988). This term has been mainly used as a design concept for the incorporation of ecological features such as 'corridors' and 'networks' into human infrastructure design (Morrish, 1995; Xuesong and Hui, 2008). However, some authors have suggested that ecological infrastructure can also be used to depict an underlying framework that supports the terrestrial and aquatic ecosystems and the ecosystem services that flow from them (Postel, 2008).

The essential feature of this concept of ecological infrastructure is connectivity (Ward and Stanford, 1995; Soule et al., 2004; Arthington et al., 2006). Maintaining ecological connectivity is the key to retaining ecosystem integrity. A certain level of ecological integrity is required to form and uphold the ecological supply chain, which produces ecosystem services required for human well-being (Mooney, 2010). A holistic approach to ascertain the true value of ecosystems must therefore consider them in terms of their contribution to the integrity of the surrounding ecological infrastructure, as well as the value of the goods and services they provide for human use.

An Earth System Stock-Flow and Fund-Service Framework for Resource Management

Here we describe recent advances in synthesizing the natural capital and ecosystem service concepts into a single framework and develop ideas about ecosystem service units, as called for by Potschin and Haines-Young (2011); we call these units ‘fund-service resources’ (Georgescu-Roegen, 1971). Dominati et al. (2010) was the first to attempt this for soils, recognizing the importance of bringing stocks and services into a single framework. More recently Robinson et al. (2012) have adapted the stock-flow, fund-service resource approach promoted in the ecological economics literature (Costanza and Farley, 2010; Daly and Farley, 2011). This framework draws on concepts developed by Georgescu-Roegen (1971) and further advanced by Daly and Farley (2011). A conceptual diagram is presented in Fig 3 for the earth system compartments or spheres. Much of the focus to date has been on the biosphere, but an earth system approach is required to capture all the relevant scales. The stock-flow resources are the tangible goods that can be used/extracted at a rate subject to availability, stockpiled and moved around the earth-system, they are materially transformed into a product, and measured by units of that product (Fig 3. (1, shown by green arrows)). Mankind harvests these stocks, which are converted to manufactured products e.g. wheat into bread, or nitrogen into fertilizer. Eventually these stocks flow back into the ecosystem either as inputs or waste (Fig 3. (2&3)). Fund-service resources produce services that are used only at a given rate, are intangible, cannot be stockpiled, and do not become a component of a product, (Fig 3. (4, and shown by blue arrows)); they are emergent, arising from a fund-service resource in response to processes (5). As they are intangible there is no return flow back into the ecosystem *per se*. However, the processing of waste from human activity, shown in the diagram as waste absorption capacity, is a regulating service, provided by a fund-service resource, which acts on stocks returning to ecosystems from the anthroposphere. Daly and Farley (2011) drew particular attention to the waste absorption and cycling services. These are critical in the functioning of the earth system as waste assimilation is a rate-limited process, and over burdening will result in pollution. Soils are important in facilitating waste assimilation, as like water and the atmosphere they are one of the major receptors for human waste. Recognizing that soils act as a fund-service resource that can only transform wastes at limited rates is important in avoiding pollution, and the only way to increase the capacity of soils to deal with waste is to build up the soil’s natural capital, rather than degrade it.

Figure 4 extends these concepts, mapping them on to basic earth-system compartment classifications. The chosen classifications are illustrative, but the key point is that it is the combination and interaction of these, termed the ‘fund-service units’ that creates the basic unit for ecosystem service delivery. This is where ecosystem concepts are important, because of their holism. It extends from the community of living organisms in conjunction with the nonliving components of their environment, across the critical zone from bedrock to the tree tops. Fund-service resource units will form a fund-service resource assemblage on the landscape, comprised of the ecological infrastructure, the size of which can be chosen depending on the scale of the goods or services of interest (e.g. watershed, wetland). For instance those interested in the provision of timber may consider the scale of the forest as the fund-service resource assemblage, whilst researchers investigating climate may focus on the entire earth-system for global scales. The schematic diagram (Fig. 4) indicates how the stock-flow and fund-service resources map onto the ecosystem service classification of the provisioning, regulating and cultural services. Like (Haines-Young and Potschin, 2010) we do not include supporting services as there is no direct human consumption of them or direct benefit from them. Differentiation between a harvested stock-flow resource and a provisioning service is highlighted using the case of food. Humans harvest pine cones to eat pine nuts. The cone is discarded after the nuts are removed and returned to the environment as waste. Pine cones are therefore the stock–flow resource, the forest is the fund-service resource assemblage, and the flow is the yield of pine nuts per unit area per year. Other common stock-flow resources are shown as trees felled, or peat extracted in the case of soils.

Value, Price and Challenges for Valuation

An added component of an ecosystem services approach is the addition of economic valuation onto the functional description of soil and ecosystem processes. Economic valuation is not to be confused with price, and it is important to draw the distinction between the two: price is determined by the intersection of supply and demand, value is not; value does contribute however, by determining what the demand is. As another example, entry into a national park might be free, but it does not mean that it is without value. Economic value is usually monetized, and it is certainly helpful when dealing with resource use options. Another useful definition of value states that ‘value is simply that quality of an object that permits measurability and therefore comparability’ (Robertson, 2012). It is often setting this comparability which is important in decision making with regard to resource use. This is an important rationale for economic valuation.

Edwards-Jones et al., (2000) argue that there exist important rationales for documenting economic ecosystem service values, because:

- They highlight the importance of ecosystem functioning for mankind.
- They reveal the specific importance of unseen, unattractive or unspectacular ecosystems.
- At a local level they can aid in identifying ecosystem services and acting as a help to decision making.
- They can aid in understanding the impacts of change and they can feed information back to models to improve our understanding of ecosystem function
- They serve as a way of communicating value by translating to a common reference such as monetary value.

The first two of these are of particular relevance to soil and vadose zone science, which often has difficulties expressing and conveying the importance of soils for humanity and earth's life support. In terms of using valuation operationally, any economist would ask what is the valuation for? Three distinct contexts can be identified for ecosystems. It is for linking value into national accounts (Harris and Fraser, 2002). It can aid decision making through cost-benefit analyses (Hansjürgens, 2004). And it can be used in making payments for ecosystem services (Farley and Costanza, 2010).

Valuation presents a range of challenges, one of which, regarding the cost-benefit approach for decision making is identifying all the different costs and benefits. What is a cost to one, may actually be a benefit to another. This is why valuation for decision making is context dependent, and goes back to the question, 'valuation for what?'

A rudimentary calculation was made by Clothier et al. (2008) suggesting that the global value of the ecosystem services provided by macropores in soil was US$304 billion per year. Here we explore this a little further and show that macropores can either provide a valuable nutrient regulation service by limiting leaching losses, or indeed they can supply a degradation process by enhancing the preferential loss of nutrients. The distinction between service and degradation process depends on whether the source of the nutrient is endogenous, that is it is generated within the soils matrix by mineralisation, or whether it is applied exogenously to the soil's surface.

For the surface soil in an apple orchard, Kim et al., (2011) found the endogenous nitrogen mineralisation from within the soil's matrix amounted to 0.12 mg-N kg^{-1} y^{-1}. This then is equivalent to the generation of 105 kg-N ha^{-1} y^{-1}. Green et al. (2010) measured the leaching of nitrogen under two apple orchards, one with standard and the other with dwarf trees, using six tension drainage fluxmeters at each site. The annual leachate losses in the standard and dwarf apple orchards were 9 and 14 kg-N ha^{-1} y^{-1} (Figure 5). Despite some 700 mm of drainage over that year, only 8-13% of the endogenously generated nitrogen was leached below the roots and into the vadose zone. The macropores in the soil resulted in the by-pass flow of the incident rainfall, thereby avoiding contact with the nitrogen generated within the soil matrix. Here the macropores have performed a valuable regulating service by ensuring that the nitrogen would be available for the trees.

With grazing cows, urine patches represent an intense local application of nitrogen, up to 1000 kg-N ha^{-1} within the 'footprint' of the patch. These patches may only cover less than 5% of the grazed field, but over a year they might occur over about a quarter of the field (Cichota et al., 2010). Locally within the patch this represents an intense exogenous application of a plant nutrient. Cichota et al. (2010) studied the leaching of nitrogen from urine patches in four lysimeters. They applied 1000 kg-N ha^{-1} of 'urine' to the surface of four lysimeters and monitored drainage at the base over the eight months of winter and spring. There was 700 mm of drainage, as there was in the orchard example above. The cumulative nitrate leaching results are shown in Figure 6. Much of the applied nitrate was leached below the rootzone, such that some 45-65% was lost to the soil-plant system and despatched further into the vadose zone. Here, a significant fraction of the exogenously applied nitrogen was available at the surface to be picked up by the rainfall and preferentially transported through the macropores, thereby avoiding being taken up by the plant whose roots ramify the soil matrix. So the value of the nutrient regulating service provided by the vadose zone's buffering and filtering capacity is low, and results in the degradation process of potentially contaminating the underlying groundwater. With agricultural intensification in New Zealand many dairy farms are stocked at 4-5 cows per hectare, and the losses from urine spots mean that the non-point source load from the sum of all these point sources can lead to high nutrient leaching rates to ground and surface waters.

These contrasts in the performance of the soil's regulating services to the vadose zone highlight the complexity of trying to value the ecosystem services provided by the soils of the rootzone of plants. Challenges exist in both identifying services and degradation processes, their adverse effects, and projecting how these may change into the future.

Applications:

Global and National Scale Resource Use

Ecosystem service assessment requires not only an understanding of the state of ecosystems, but more critically the change that occurs, especially given projected changes in drivers, such as land use or climate change. In order to achieve this assessment, models play a central role in providing the capability to forecast the expected impacts of decisions. Decision support tools have been, and are, an important scientific and research product. With regard to the assessment of natural capital and ecosystem services there is a strong emphasis on the development and use of biophysical models that predict ecosystem change, both in space and time and at a range of scales.

At a global scale, GUMBO (the global unified metamodel of the biosphere) is an example of an earth system biophysical and economic model that attempts to assess the dynamics and values of ecosystem services (Boumans et al., 2002). It makes a bold attempt to model the earth system in an integrated way by incorporating both the biophysical characteristics of the earth system and the socio-economic aspects of man's activities. The model includes various components to simulate water, carbon, mineral and nutrient fluxes through the lithosphere, hydrosphere, biosphere and atmosphere. The pedosphere is not dealt with as an explicit module, but is included in the lithosphere. There are predictions of the rate of soil formation, plus carbon and nutrient fluxes and weathering and erosion processes. The hydrosphere and biosphere modules deal with the unsaturated vadose zone. The model then divides the earth's surface into the 11 biomes of open-ocean, coastal ocean, forests, grasslands, wetlands, lakes/rivers, deserts, tundra, ice/rock, croplands, and urban area. These might be considered the fund-service resource assemblages. Material and energy flows around the earth system as stock-flow resources, some of which are harvested into the anthroposphere. These can be returned as waste or manufactured capital, as shown in Fig. 4. The purpose of such models is not to predict every aspect of the earth system, but to give some indication of the direction and magnitude of potential change, given different policy scenarios. A number of predictions are presented in Fig 7 showing the biophysical outputs for soil formation and nutrient cycling. These can be assigned an economic price, allowing cross comparison for example with energy prices. Surprisingly, soil formation simply shows a downward decline, which is perhaps an artefact of the way it is determined. A common assumption at these scales is that soil formation is a combination of geochemical rock weathering and organic matter accumulation. However, many soils form from regolith or after the deposition of sediments, either alluvial, wind-blown, or increasingly mankind's earth-moving activities (Wilkinson, 2005). Soil formation therefore occurs on this 3D regolith, rather than as the regression of a 2D rock surface. The model perhaps indicates an important knowledge gap. What are the rates of soil formation at a global scale, and how will man's activities influence these rates? Pricing, as we might expect, follows energy prices to some extent (Fig 7), but it does raise the question of how, and which, soil services we value.

At the national and regional scales, a number of models are rapidly being developed using different architectures and approaches to assess ecosystem services (Vigerstol and Aukema, 2011). One such model is MIMES (the Multiscale Integrated Earth Systems Model) as summarised in Boumans and Costanza (2007). This builds on the GUMBO model. However, InVEST (Integrated Valuation of Ecosystem Services and Tradeoff tools) is perhaps the most advanced model in this regional scale category, using production functions as the basis for modelling ecosystem services, with examples of development scenarios run for the Willamette Basin in Oregon (Nelson et al., 2009). Another model gaining increasing exposure in the ecosystem services arena is ARIES (Villa et al., 2009) (ARtificial Intelligence for Ecosystem Services). This maps the potential provision locations of ecosystem services ("sources") their users ("use"), and biophysical features that can deplete service flows ("sinks") using deterministic ecological process models, or *ad hoc* Bayesian models" (ARIES, 2013).

The availability of soil property data is likely to present a constraint on such modelling approaches as soil maps present a snap shot of soil properties in time. Quantification of soil change at these scales are limited to a few national surveys such as the Countryside Survey in the UK (Emmett et al., 2010; Robinson et al., 2012). The SoilTrEC team in the EU is trying to address this issue of understanding and incorporating the dynamics of soils into regional scale models, and it is rapidly developing the CAST (coupled, Carbon, Aggregation and Structure Turnover) model (Banwart et al., 2012). CAST focuses on describing aggregate dynamics, with aggregate structure being seen as a key property to be maintained for mineral soil health.

Intermediate and Local Scale Land Use Decision Making

One of the limitations of regional scale models is that in order to parameterize them, the geometry of the landscape must be simplified or aggregated. These can result in an inability to represent properly the pathways of both stock, and service flows. This may, or may not, be such a major limitation for decision making at the regional or national scale, but it does become an important issue at farm and intermediate scales. This is especially so if pathways are incorrectly represented, for the modelled interception of stock-flow resources and services may be erroneous. For example, soils with high storage or high infiltration capacity have the capacity to mitigate floods, and reduce sediment loads to water bodies and built infrastructures. They can decrease lateral, yet increase vertical movement of chemicals by acting as a sink for the fast moving overland flow and near-surface subsurface flow. They can either store this water, or route it more slowly through subsurface routes. The function of such elements within the landscape on runoff changes depends on their spatial placement. Elements with negligible "up-hill" contributing areas have far less impact than those receiving contributions from low-permeability areas (Jackson et al., 2008).

The LUCI (2013) (Land Utilisation and Capability Indicator) model, a second-generation extension and software implementation of the Polyscape framework is described in Jackson et al. (2013). It was developed to overcome this limitation. It is specifically tailored to investigate the impact of farm scale interventions on catchment scale function. LUCI estimates a variety of ecosystem services which depend significantly on soil function. These include namely agricultural productivity, carbon sequestration, floods, erosion, sediment transfer, and habitat. Tradeoffs and synergies between individual service provisions are also considered. LUCI explicitly tracks the lateral as well as vertical movement of mass (water, sediment and chemicals) through the landscape at spatial resolutions on the order of meters. Although this more sophisticated treatment of hydrological fluxes is computationally more expensive, some novel algorithms have been developed and implemented within LUCI to reduce significantly the normal cost of such an approach. There does appear to be future potential to extend the scales considered within ecosystem service models to include the impact of multiple subfield scale interventions which can be analysed at the regional scale.

Figure 8 shows an example of LUCI maps for a variety of soil-reliant provisioning ecosystem services, along with maps of where trade-offs and synergies exist between services for the 12.5 km^2 Pontbren catchment in mid-Wales, which might be considered the fund-service resource assemblage in this case. Details on the physical characteristics of the catchment can be found in Marshall et al. (2009). In brief, land cover consists mainly of 'improved' pasture, semi-natural, unmanaged moorland, mature woodland and tree plantations. Agricultural soils in the catchment have high clay contents and are generally relatively impermeable, with less intensively farmed moorland having higher organic matter content. Elevation ranges between 170m and 425m a.s.l. LUCI is used to identify where opportunities to improve carbon sequestration, reduce erosion, improve water flow, water quality and biodiversity exist, while still maintaining farm productivity and hence livelihoods. We find that increasing the number of services under consideration generally increases the amount of land where trade-offs in service provision exist. However, where services are more interlinked, as for example with flood mitigation, erosion and carbon sequestration, more synergies in service provision exist. Hence large proportions of land provide multiple existing services, or conversely they provide an opportunity to increase the provision of multiple services. For example, increasing organic matter content in soils not only reduces CO_2 emissions, but also increases the water holding capacity and infiltration capacity. This leads to flood and drought alleviation and increased soil structural stability. In turn, this results in reduced erosion, increased crop yields and greater plant biomass, thereby increasing nutrient reserves and enhancing biodiversity in soil ecosystems.

These modelling approaches are useful in identifying data and knowledge gaps in soils information. A major limitation is the lack of spatial and temporal data on the changes in soil properties with land-use change. Much of the work of the previous century focused on soil mapping for inventory, where static properties were the focus. Current environmental issues require both the understanding and mapping of soil dynamics, especially to determine how both natural and anthropogenic activity change soil properties and stocks (Richter et al., 2011; Robinson et al., 2011). Fundamental questions need to be addressed, such as how deep is the soil and the vadose zone (Richter and Yaalon, 2012)? How do they vary in space and time? The description of the soil should not be limited by 1 or 2m boundaries imposed for resource inventory mapping. This is important because it impacts on the parameterization ability and the prediction capability from our hydrological process models. Combining rooting depth data (Canadell et al., 1996) with habitat data may serve as a first approximation for mapping soil depth. If combined with hydropedological models this may serve as a more realistic research direction. Rates of soil formation and turnover are also poorly addressed at regional and global scales. Much of pedology has focused on the processes governing the slow formation of soils over time that lead to the distinctive horizonation that we see. There is however, an urgent need to understand the rates of soil formation and loss which result from anthropogenic activities, ranging from semi-natural systems, through agro-ecosystems, to urban systems. The limited data available on rates of soil change tend to be confined to arable systems with loamy soils. There is a need to broaden this information (Richter and Markewitz, 2001). Increasingly it is likely that this type of information on soil stocks and services, and their changes on anthropogenic time scales, will be used to aid both land management and land use decisions, which as a result of pressure on the finite resource that is land, will increasingly extend to legal arguments in judicial hearings.

Natural Capital in the Environment Court

The horticultural industries of New Zealand annually generate $3.5 billion of export revenues and contribute another $1.5 billion to the domestic economy (www.freshfacts.co.nz). This $5 billion industry covers just 70,000 hectares of land, and it is often prime high class land with versatile soils on the periphery of cities. This small area of land not only provides a provisioning ecosystem service of $5 billion, but also it provides other valuable, regulating and cultural services. New Zealand's urban areas and built infrastructures cover nearly 1 million hectares of land, and every year there is a loss of 40,000 hectares of productive lands to peri-urban expansion (Mackay et al., 2011). The range and value of the ecosystem services that flow from urban areas are very different from those provided by horticultural lands.

Legislation around the world seeks to protect natural and physical resources. In 1991, New Zealand passed innovative and omnibus legislation to deal with environmental and developmental issues: the Resource Management Act (RMA). Section 5 details that the '... purpose of this Act is to promote the sustainable management of natural and physical resources'. The Act would enable "... managing the use, development and protection of natural and physical resources to enable people and communities ... to provide for their social economic and cultural well being and for their health and safety while ...

- sustaining the potential and natural physical resources ...
- safeguarding the life-supporting capacity of air, water, soil, and ecosystems;
- and avoiding, remedying, or mitigating any adverse effects of activities on the environment."

It would seem that there have only been a few attempts in judicial hearings to use natural capital and ecosystem services thinking to argue about the sustainability of natural resources use and the safeguarding of life-supporting capacities. We describe one attempt in relation to the proposed peri-urban expansion of a city onto prime horticultural land.

The hardware retailer Bunnings' purchased 4 ha of orchard land on the outskirts of the town of Hastings and sought resource consent to build a large-format store. The Hastings District Council (HDC) appointed independent commissioners to hear Bunnings' application. In July 2009, the Commissioners declined Bunnings' application and stated that "... if these soils are as valuable as described, their loss should be avoided". Bunnings' appealed that decision and the appeal was heard in the Environment Court during March 2011. One of us acted as an expert witness for the respondent, the HDC (Clothier, 2011). Clothier (2011) argued that "... we cannot afford to lose such valuable natural capital assets, whose presence is needed for their ecosystem services, and whose use will be needed to enable the horticultural industries to realise their strategic goals, and whose functioning will continue to enhance the life-supporting capacities of the Heretaunga Plains", as required by the Hastings' District Council's District Plan for the Heretaunga Plains.

Moreover, Clothier (2011) noted that "several key ecosystem services are provided by the soil of this site: primary production, nutrient cycling, water storage, platform, and water supply regulation" for the vadose zone which is linked to the nearby Karamu Stream. He added "that this deep soil has no impeding layers of low conductivity which means that it can provide the ecosystem service of water supply regulation" to the Karamu Stream, which a hard, impermeable surface of a large-format store and its car-park could not.

Also, Clothier (2011) stated that "... horticulture and agriculture on elite soils on the Heretaunga Plains enable a wide range of provisioning ecosystem services for the district.

The biodiversity of the Hastings District reflects its natural history and more recently the significant development of horticulture. The loss now of this horticultural land, would result in a loss of refugia for elements of the horticulturally-based biodiversity which provides the Hastings District with its distinctive and valued character".

However, an expert witness for Bunnings argued that "... the concept of natural capital value was still an emerging discipline" and that the concept of natural capital was in his view "... unhelpful in terms of the issue confronting this Court. That issue is, as expressed in the RMA, 'safeguarding the life supporting capacity of the air, water, soil and ecosystems' ". Bunnings' lawyer in his closing address considered that "... there is no quantitative or qualitative analysis of the ecosystem services at the site other than in relation to food production".

The judgment (Dwyer, 2011) was cautious and noted that "... we do not propose to enter that [natural capital] debate ... but it seemed to us that Dr Clothier took a somewhat more holistic approach to assessment of the value of the soils of the site". The judgement noted that although the "... loss of 4 ha of Plains land is insignificant in itself the wider policy implications are significant." The appeal was declined, and costs awarded to the HDC. In his costs decision, Judge Dwyer (Dwyer, 2012) stated clearly that "... in reaching [our] decision we emphasised the importance of the District Plan to protect the rural resource." The latter term is, in our opinion, natural capital. That seems to imply that the rural resource needs to be protected to ensure the continued flow of ecosystem services from it. Judge Dwyer concluded that "... Bunnings considerably understated the versatile nature and capacity of the soils at the site ... In those respects, Bunnings' case might be described as without substance or unmeritorious. Bunnings will pay 50% of the costs incurred by Council".

So although Judge Dwyer and his two Commissioners did not directly buy into a natural capital argument, they did note a holistic view was needed. Holism, it seems, is an ecosystem services approach in principle, at least in a judicial sense. It would appear then that some headway has been made by the use of natural-capital reasoning in judicial proceedings in relation to the 'safeguarding the life-supporting capacity of … soil, and ecosystems" (RMA, Sect., 5). Yet, precedence in a legal sense would not, however, seem to have been registered.

Conclusions

The ecosystem services approach has been important in highlighting the lack of consideration of the economic value of ecosystem services in decision making. Here we have synthesized ecosystem services and earth system concepts, and addressed some of the typology challenges for soils identified in Robinson et al. (2011). An important challenge for the ecosystem services approach is the 'public' nature of ecosystem services. One way of overcoming this challenge is to adopt the same approach used to overcome market failures in the provision of public socio-economic services. In other words, we must invest in the underlying infrastructure that provides these services.

Bristow et al. (2010) argue that while built infrastructure investment has been ever-increasing, we have not been investing sufficiently in our ecological infrastructure and ecosystem service supply chains. Indeed, inadequate investment in ecological infrastructure has led to a worsening environmental crisis, in which critical ecosystem services have been, and are being, lost across the globe. For example 60% of ecosystem services examined by the MEA (2005) were found to be degraded. 'Public' ecological infrastructure will continue to be fragmented and destroyed if we continue to undervalue and under-invest in it.

A likely consequence of improving the management of public goods is that we will require new or restructured institutions to manage resources and services at appropriate scales. The difficulty illustrated by the lack of agreement and consensus on how to tackle climate change, a global problem, demonstrates this. The development of institutions is not the remit of most scientists. However, there are important contributions to be made through informing the debate about the appropriate scale of management of different ecosystem services, along with the development of decision support tools and data sets that inform policy and provide support in judicial hearings to protect, restore or enhance ecological infrastructure.

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Table 1. Soil ecosystem services modified from Robinson et al. (2012)

Stock-flow resource Provisioning goods	Ecosystem-service Regulating service	Ecosystem-service Cultural service
Topsoil	Climate regulation	Sports and recreational fields
Sub soil	Buffering extremes of heat and cold	Preservation of historic artifacts
Peat	GHG regulation	Cooking
Turf / sod	Hydrological regulation	Burial grounds
Sand / clay minerals	Buffering floods and droughts	Aesthetic landscapes
Biomedical resources	Water filtration	Spiritual
Bio-resources, soil stabilizers	Hazard regulation	
	Structural support buffering, shrink/swell	
	Landslides/slumps	
	Liquifaction	
	Dust emissions	
	Disease regulation	
	Human pathogens	
	Disease transmission and vector control	
	Biodiversity	
	Gene pool	
	Pathogen regulation	
	Waste processing	
	Cleaning, degrading, transforming	

Figures

Figure 1. Number of references to ecosystem services and natural capital etc. showing exponential growth and the link between terms; from Dick et al. (2011).

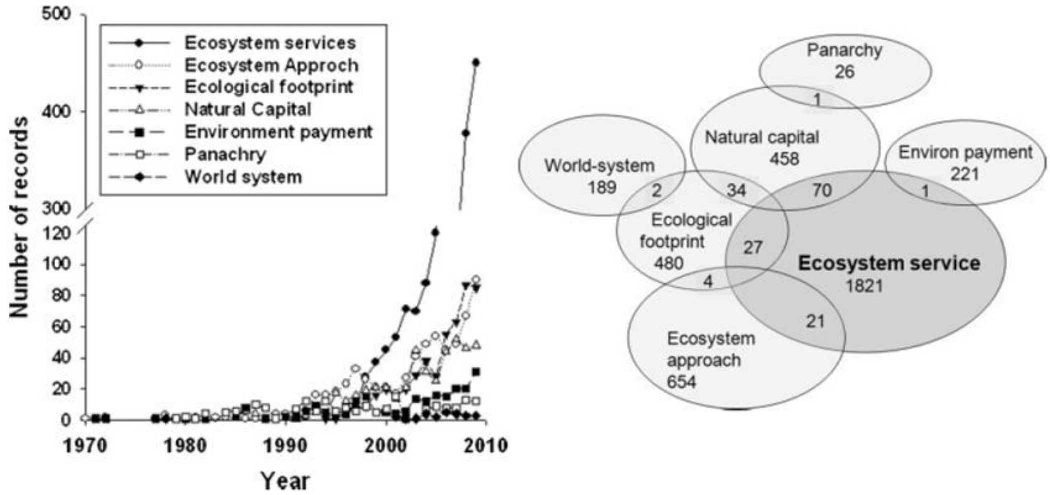

Figure 2. Pedosphere natural capital and their internal cycling between abiotic and biotic components. Modified from Robinson et al. (2012)

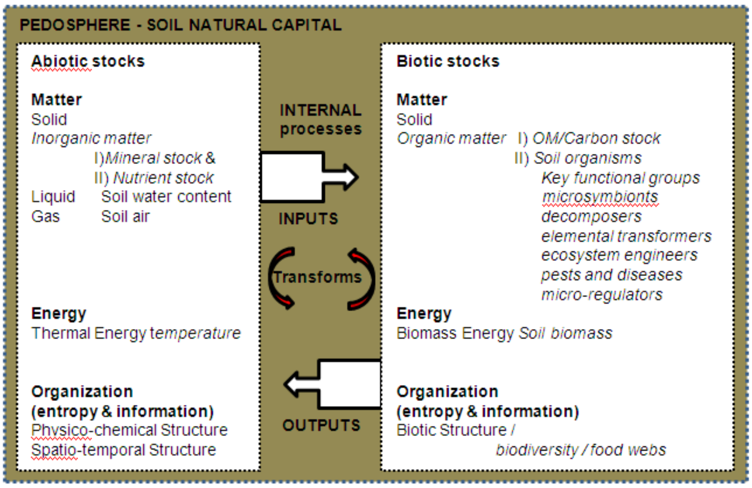

Figure 3. Earth system model of the spheres from which we draw natural resources and obtain ecosystem services. Humans harvest goods (1, stock-flow resources) into the anthroposphere which may return as waste (2) or be transformed into a capital input (3). The interaction of the earth system spheres results in emergent fund-services (4) derived from the fund-service resources (5).

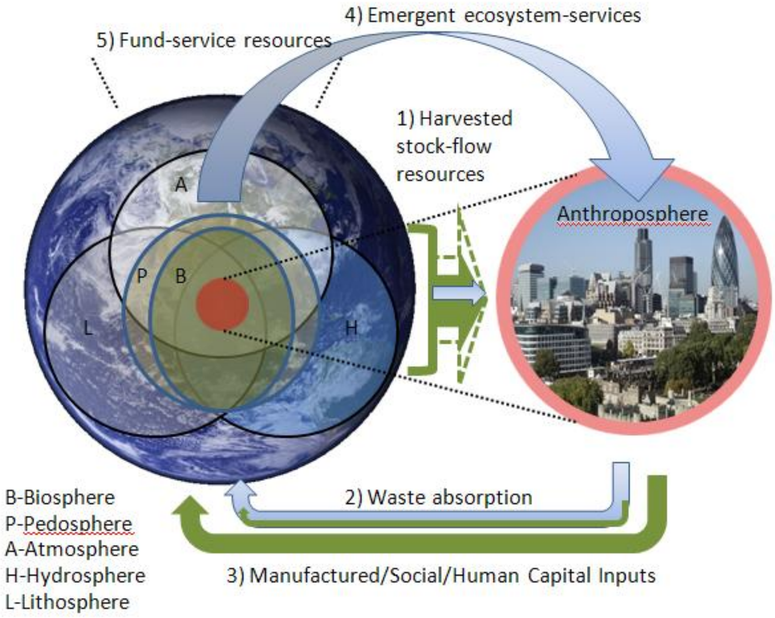

Figure 4. Fund-service resource units, and fund-service resource assemblages derived from the combination of earth system components/spheres. The relationship between the stock-flow resource, fund-service resource and MEA (2005) provisioning, regulating and cultural services is shown in the bottom schematic diagram.

Earth system compartments / spheres

Lithosphere (Rock types)	**Pedosphere** (Soil orders)	**Terrestrial Biosphere** (Biomes)	**Hydrosphere Aquatic** (Biomes)	**Atmosphere** (Layers)
Sedimentary Igneous Metamorphic	Alfisols Andisols Aridisols Entisols Gelisols Histosols Inceptisols Mollisols Oxisols Spodosols Ultisols Vertisols	Desert Forest Grassland Tundra	Fresh water Marine	Troposphere Stratosphere Mesosphere Ionosphere Exosphere
Shale	Histosol	Forest		Troposphere
Sandstone	Inceptisol	Forest		Troposphere
Shale			River	Troposphere
Shale			Lake	Troposphere

Fund-service resource unit

Fund-service resource assemblage, e.g. watershed

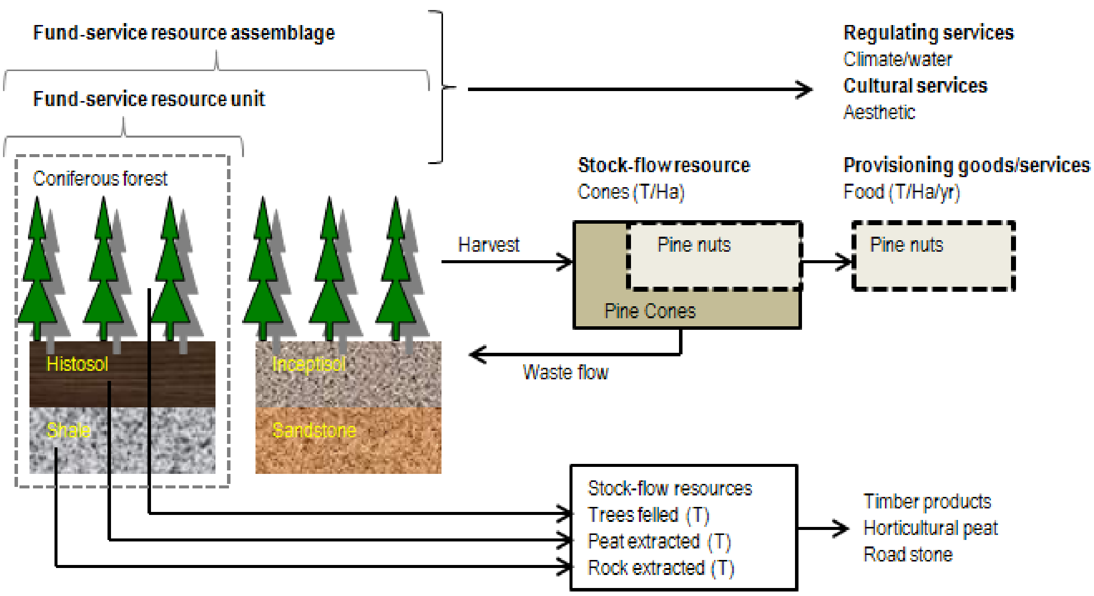

Figure 5. Top: The time series in the mean of the cumulative nitrate leaching under apple (grey circles) and dwarf apple (open circles) as measured by a set of 6 tension drainage fluxmeters at each orchard site during 2009 (after Green et al., 2010)

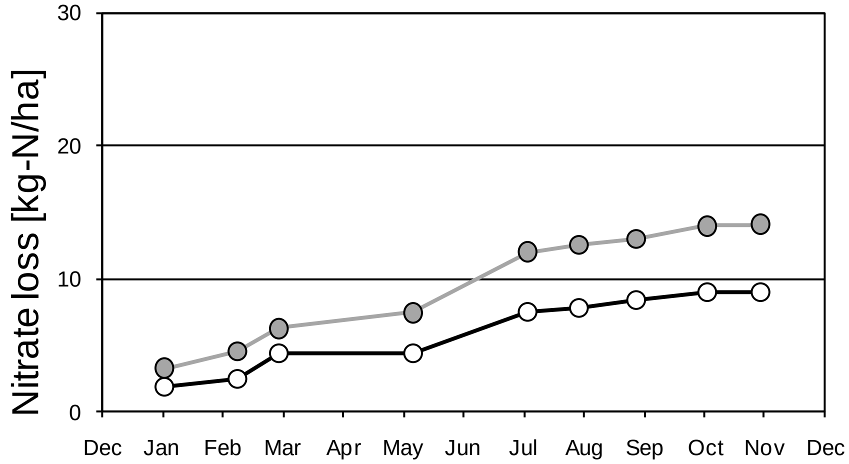

Figure 6.The cumulative nitrate leaching from 4 lysimeters to which had been applied urine to simulate a ‘urine patch’ at a concentration of 1000 kg-N/ha (from Cichota et al., 2010)

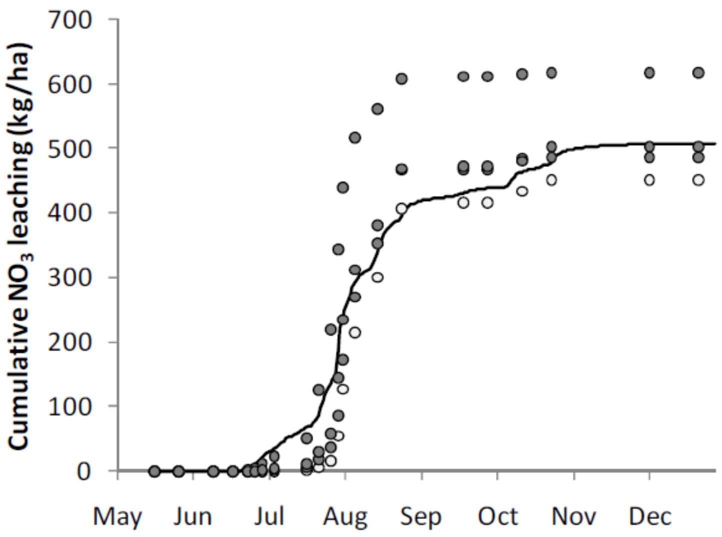

Figure 7. GUMBO predictions for soil formation, nutrient cycling and energy prices; altered from Boumans et al., (2002). These scenarios include a Base Case (using the ‘best fit’ values of the model parameters over the historical period). Star Trek, technologically optimistic policies (higher rates of consumption and investment in built capital, lower investment in human, social and natural capital), the real state of the world corresponds to the optimistic parameter assumption set (new alternative energy comes on line, etc.); Mad Max, technologically optimistic policies and the real state of the world corresponds to the skeptical parameter assumption set; Big Government, technologically skeptical policies (lower rates of consumption and investment in built capital, higher rates of investment in human, social and natural capital) and the real state of the world corresponds to the optimistic parameter assumption set, and EcoTopia, technologically skeptical policies and the real state of the world corresponds to the skeptical parameter assumption set.

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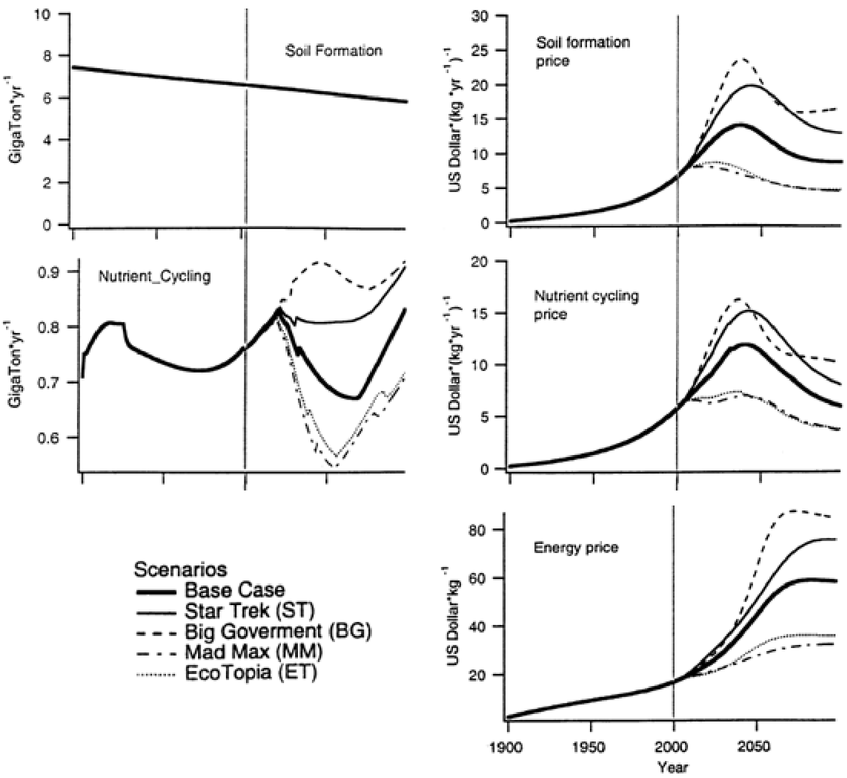

Figure 8. Example LUCI application: Single service provisions and tradeoffs/synergies between service in the Pontbren catchment, mid-Wales.