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Analysis

A framework for classifying and quantifying the natural capital and ecosystem services of soils

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ABSTRACT

The ecosystem services and natural capital of soils are often not recognised and generally not well understood. This paper addresses this issue by drawing on scientific understanding of soil formation, functioning and classification systems and building on current thinking on ecosystem services to develop a framework to classify and quantify soil natural capital and ecosystem services. The framework consists of five main interconnected components: (1) soil natural capital, characterised by standard soil properties well known to soil scientists; (2) the processes behind soil natural capital formation, maintenance and degradation; (3) drivers (anthropogenic and natural) of soil processes; (4) provisioning, regulating and cultural ecosystem services; and (5) human needs fulfilled by soil ecosystem services.

1. Introduction

Nowadays industrial and post-industrial economies seem less dependent on their environment; however, to meet the basic needs of a growing global population (food, fibre, clean air, clean water), the extreme importance of the natural capital stocks and ecosystem services they provide needs to be recognised. Accordingly, since the late 1960s there has been a growing interest in the analysis of the services provided by ecosystems and the need to include them in decision-making processes in order to achieve sustainable development. Several studies have provided frameworks for the description and valuation of ecosystem services (Costanza et al., 1997; de Groot et al., 2002; MEA, 2005) but all too often soils, the basic substrate for many ecosystems and human activities, have been considered a black-box within these frameworks, because their focus is on what happens above ground. Many authors (Balmford et al., 2002; Daily et al., 1997; Kroeger and Casey, 2007; Swinton et al., 2006, 2007; Turner and Daily, 2008) agree that our ability to understand soil natural capital and the ecosystem services it provides is incomplete, despite a good understanding of soil formation and functioning. Because soils are an important determinant of the economic status of nations (Daily et al., 1997), it is essential to include them in ecosystem service frameworks that inform decision-making and environmental policies.

One of the difficulties while constructing a coherent "natural capital-ecosystem services" framework for soils is the confusion created by the use of different terminologies borrowed from at least three disciplines: ecology, economics and soil science. Many of the terms used have multiple definitions. For sake of clarity, we define here the terms as used in this paper, that are applied to soils — fully recognising that a particular term may be used differently in a different discipline or field. Fig. 1 presents an example of each term defined here in the context of the provision of an ecosystem service: flood mitigation. *Natural capital* refers to the extension of the economic idea of manufactured capital to include environmental goods and services. Natural capital, like all other forms of capital, is a stock as opposed to a flow. Natural capital consists of "stocks of natural assets (e.g. soils, forests, water bodies) that yield a flow of valuable ecosystem goods or services into the future" (Costanza and Daly, 1992, p. 38). Soils are considered here as natural capital and provide services such as recycling of wastes or flood mitigation (Fig. 1).

To describe soils, pedologists use different concepts like soil components and soil properties. A *soil component* is defined here as a biogeochemical species (e.g. nitrate NO_3^-) or an aggregation of biogeochemical species (e.g. clays, Fig. 1) that make up soils. Soils consist of four major categories of soil components: mineral, organic, liquids, and gases. *Soil properties* are the physical (e.g. porosity, texture), chemical (e.g. pH, readily available phosphate), and biological (e.g. microbial biomass) characteristics of a soil. Soil properties are often measurable quantities that allow soil scientists to place soils on relative scales. For example (Fig. 1), clays are soil

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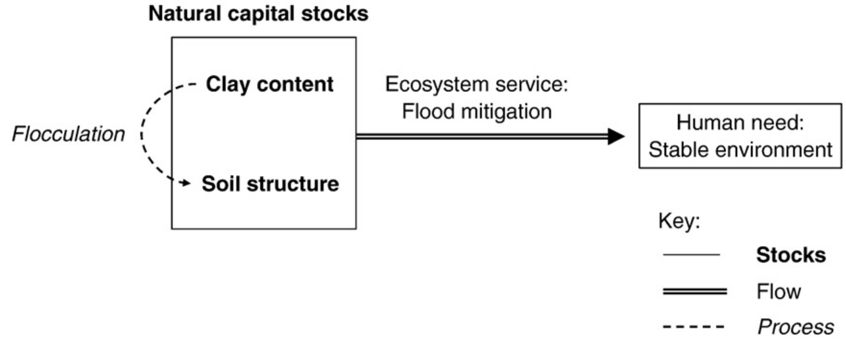

Fig. 1. Illustration of the use of the key terms employed in this paper.

components which play an important role in the formation of soil structure. Clay content is a property informing the amount of clay in a soil.

Authors (Costanza and Daly, 1992; Daly and Farley, 2003; de Groot et al., 2002; Ekins et al., 2003a) agree that natural capital yields ecosystem services but the nature of these ecosystem services is still debated in the literature (Costanza 2008; Fisher & Kerry Turner 2008; Wallace, 2007). Controversy revolves around the definitions of the terms "function" and "processes" used to define ecosystem services and the boundaries between them. In ecology, the traditional definition of an ecosystem function was the role the ecosystem plays in the environment, but in recent years, the term "ecosystem function" has been used as a synonym for "ecosystem process" (Wallace, 2007), as in soil science. In this paper, the term "process" is used rather than "function" and is defined as the transformation of input into outputs. Some processes are chemical (e.g. oxidation), some physical (e.g. diffusion), others are biological (e.g. denitrification). For example (Fig. 1), flocculation is a process leading to the formation of soil structure. At the molecular level, water molecules and cations link negatively charged clays together. When the soil dries out the clays are brought together into more stable aggregates.

The existing literature on ecosystem services tends to focus exclusively on the ecosystem services rather than holistically linking these services to the natural capital base from which they arise. To avoid this, *ecosystem services* are defined here as the beneficial flows arising from natural capital stocks and fulfilling human needs. We argue that ecosystem services are not processes but flows (amount per unit time), as opposed to stocks (amount). For example (Fig. 1), soil structure presents pores able to store water. The provision of the ecosystem service 'flood mitigation' depends on the amount of water a soil can store (stock) and also the timing of the availability of the storage volume regarding a rainfall event.

Keeping in mind these concepts, this paper undertakes to assess the importance of soils as natural capital and provider of ecosystem services. It draws on scientific understanding of soil formation, functioning and classification systems and builds on current thinking on ecosystem services to develop a framework to conceptualise, classify and quantify soil natural capital and ecosystem services. The paper first discusses existing ecosystem service frameworks, then presents a new framework that introduces soils as natural capital, illustrates natural capital formation, maintenance and degradation and the drivers impacting on these processes. Finally, the paper describes the ecosystem services provided by soils, and outlines how soil ecosystem services fulfil human needs.

2. Existing Classification Schemes for Ecosystem Services

Before presenting our framework, we examine the strengths and limitations of the general ecosystem service frameworks found in the literature, as well as agro-ecosystems service frameworks which include soils.

2.1. General Ecosystem Service Frameworks

With heightening awareness of the importance of ecosystem services, over the last two decades general typologies and classification systems have emerged (Table 1). De Groot's classification system (1992), one of the first, defined ecosystem functions as "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly" and grouped these functions into four primary categories: regulation, habitat, production and information functions (Table 1). Costanza et al. (1997) detailed seventeen goods and services, including most of de Groot's (1992) functions. Noël and O'Connor (1998) classified "the specific roles or services provided by natural systems that support economic activity and human welfare" into five categories — "the five S's" (Table 1). Daily (1999) also produced an "ecosystem services framework" including five services (Table 1). A common thread through all these classification systems is the recognition of the diversity of roles played by ecosystems (Table 1). The concepts proposed in different classifications tally with each other (Table 1), for instance de Groot's (1992) production functions correspond to what Noël and O'Connor (1998) called the "source" role of ecosystems.

More recently, de Groot et al. (2002) identified 23 functions in the four primary categories established in earlier work (de Groot, 1992) and detailed the corresponding processes and services, noting that "ecosystem processes and services do not always show a one-to-one correspondence" (de Groot et al., 2002, p. 397). To the four categories, they later introduced a fifth, a carrier function (Table 1) and specified that the "regulation functions provide the necessary pre-conditions for all other functions" (de Groot, 2006, p. 177). As part of the CRiTiNC project, Douguet and O'Connor (2003) and Ekins et al. (2003b) used a similar classification (Table 1) to that of Noël and O'Connor (1998) to argue that the principles of environmental sustainability must be based on the maintenance of the important life-support "functions of nature" that form the basis on which the "functions for people" are fundamentally dependent.

The novel idea that de Groot et al. (2002), Douguet and O'Connor (2003) and Ekins et al. (2003b) advanced is that some ecosystem functions – or processes as we call them here – support others. Ecosystem processes insure ecosystems health and functioning, whereas ecosystem services are flows coming from these ecosystems. The Millennium Ecosystem Assessment (MEA, 2005) took up this idea in a "framework of ecosystem services" (Table 1). It assessed the consequences of ecosystem change for human well-being, defining ecosystem services as "the benefits people obtain from ecosystems" (MEA, 2005, p. 40). It classified ecosystem services in four categories: provisioning, regulating, cultural and supporting services. The first three categories of services directly affect people, whereas the supporting services are there to maintain the other services. It is interesting to point out that the MEA's four categories are close to the categories of functions of de Groot (1992) with the difference that de Groot's "regulation functions" seem to include both of the MEA's

Table 1
Ecosystem roles mentioned by different classification systems.

Authors	Ecosystem roles[a]					
	Life-support	Production	Regulation	Habitat provision	Physical support	Information and culture
De Groot (1992), de Groot et al., (2002)	Regulation functions	Production functions	Regulation functions	Habitat functions	NC	Information functions
Noël & O'Connor (1998)	Life-support	Source	Sink	NC	Site	Scenery
Daily (1999)	Regeneration processes	Production of goods	Stabilising processes	NC	NC	Life filling functions, preservation of options
Ekins et al. (2003a,b)	Life-support	Source	Sink	NC	NC	Human health and welfare
MEA (2005)	Supporting services	Provisioning services	Regulating services	NC	NC	Cultural services
De Groot (2006)	Regulation functions	Production functions	Regulation functions	Habitat functions	Carrier functions	Information functions

[a] Roles as described by the original authors. NC: not considered.

"supporting and regulating services" (Table 1). The approach set out in the MEA has been adopted and used widely (Barrios, 2007; Lavelle et al., 2006; Sandhu et al., 2008; Swinton et al., 2007; Zhang et al., 2007).

Some roles of ecosystems are mentioned unanimously by the authors cited above (Table 1), including the production (or source) role — the capacity of ecosystem to produce resources of interest for humans; the regulation role — the capacity of ecosystems to auto-regulate themselves, absorb human emissions, recycle them, and remain stable; and the information role — the capacity of ecosystems to inspire people and produce non-material goods. However, as has been reported by a number of authors (Boyd and Banzhaf, 2007; Costanza, 2008; Fisher and Kerry Turner, 2008; Wallace, 2007), some common challenges are still found with existing frameworks.

First, not all existing frameworks recognise that some processes sustain others. Of the classification systems covered (Table 1), only Ekins et al. (2003b), de Groot (2006), and the MEA (2005) acknowledge that some processes "support" other processes. Failure to make the distinction can lead to double accounting in the valuation and measurement of ecosystem services. Once it has been recognised that some processes support others, the challenge is to identify precisely the ecosystem services provided and the processes directly supporting them and to base the valuation of the services on these processes.

Second, the definitions and use of terms to describe ecosystem services vary across the published classification systems. The ecosystem services literature often refers to groups of processes such as, for instance, "nutrient cycling" (MEA, 2005) as a service. It has been argued (Balmford et al., 2008; Boyd and Banzhaf, 2007; Fisher and Kerry Turner, 2008; Wallace, 2007) that doing so mixes up the "means of production", the processes, with the actual services. Photosynthesis, for example, is an essential process for plant growth and should not be confused with the ecosystem service it supports, which is the provision of food and fibre.

Third, as different authors (Boyd and Banzhaf, 2007; Wallace, 2007) have pointed out, in valuing ecosystems it may be more helpful to focus on ecosystem components, and use them as proxies for services, rather than on processes, because science gives us much more information on the structure and composition of ecosystems than on the processes involved in their functioning.

The general ecosystem service frameworks (Table 1) do little justice to the roles of soils in the provision of ecosystem services and as a consequence fail to recognise the large differences that exist between soils in their ability to provide services. For instance, the MEA mentions "soil formation" as a supporting service and recognises that "many provisioning services depend on soil fertility" (MEA, 2005, p. 40). It also mentions the role of soils in the provision of regulating services like erosion regulation, water purification and waste treatment, but does not explicitly identify the part played by soils in the provision of these services and more generally in the provision of services from above ground ecosystems. This is why we need to examine ecosystem service frameworks that accord more importance to soils and their different roles.

2.2. Soil Ecosystem Service Frameworks

Many agree (Daily, 1997; Dale and Polasky, 2007; de Groot et al., 2003; Straton, 2006) that a better characterisation of ecosystem services supplied by soils is overdue. Daily (Daily et al., 1997, p.128) indicated that "research is needed to better characterise the ecosystem services supplied by soils", along with a better understanding of the "interrelationships of different services supplied by soils and other systems". While a few authors (Daily et al., 1997; Wall et al., 2004; Weber, 2007) have proposed soil specific frameworks for ecosystem services, others (Barrios, 2007; Lavelle et al., 2006; Porter et al., 2009; Sandhu et al., 2008; Swinton et al., 2007; Zhang et al., 2007), mainly working on wider agro-ecosystems, have detailed services provided by soils (Table 2). These studies enable us to start identifying where and in which way soils affect the provision of ecosystem services. When comparing the different soil ecosystem service frameworks in the literature (Table 2), the following roles of soils in the provision of services can be identified:

- Fertility role: soil nutrient cycles ensure fertility renewal and the delivery of nutrients to plants, therefore contributing to plant growth,
- Filter and reservoir role: soils fix and store solutes passing through and therefore purify water. They also store water for plants to use and take part in flood mitigation,
- Structural role: soils provide physical support to plants, animals and human infrastructures,
- Climate regulation role: soils take part in climate regulation through carbon sequestration and greenhouse gases (N_2O and CH_4) emissions regulation,
- Biodiversity conservation role: soils are a reservoir of biodiversity. They provide habitat for thousands of species regulating for instance pest control or the disposal of wastes,
- Resource role: soils can be a source of materials like peat and clay.

To progress the recent advances made in soil specific ecosystem service frameworks, several remaining limitations need to be addressed. Extending the existing frameworks to show the links between soil natural capital stocks and ecosystem services to provide a more holistic approach would be one of the major challenges. Like general ecosystem service frameworks, existing soil ecosystem service frameworks fail to recognise that some processes support other processes which lead to confusion in the wording of the services. For instance, Wall et al. (2004) mention as services the "retention and delivery of nutrients to plants" and the "contribution to plant production for food" (Table 2). The first one is a group of processes, whereas the second one is the service. Moreover, existing frameworks tend to ignore a great deal of scientific knowledge that has been acquired about soils and do not acknowledge the complexity of soil functioning. When applying the existing frameworks for valuation, some authors tend to use a one-to-one correspondence between processes and services without acknowledging the complexity of soil processes. Sandhu et al. (2008) and Porter et al. (2009) used similar methodologies for the valuation of ecosystem services from agro-ecosystems, including some soil ecosystem services. For each one of the services they valued, they identified one soil process underlying the service (e.g. soil formation), using one indicator to measure that process (e.g. the population of earthworms). The economic valuation was then based on that single indicator. While the methodology used in both studies helps illustrate the links between soil processes and properties and the provision of services from soils, limiting each service to one indicator fails to recognise that each soil service is the product of multiple properties and processes. Nevertheless, Porter et al. (2009) did consider a more sophisticated function when dealing with nitrogen regulation, showing that it is necessary to acknowledge that soils are very complex ecosystems. Services are underpinned by more than one process or property and the use of process-based models that capture the scientific knowledge available is required to fully comprehend them. Dale and Polasky (2007) argued about general ecosystem service frameworks that "a thorough understanding of how ecological systems function" is needed and that "ideally, it would be useful to have the ability to accurately measure the flow of ecosystem services from agro-ecosystems at several scales of resolution" (Dale and Polasky, 2007, p. 287). Existing frameworks also pay little attention to those factors over which managers of soils have control and therefore have had limited utility as tools to explore the impacts of land uses and practices on the provision of soil ecosystem services.

The limitations of existing frameworks mentioned above highlight the need for a better framework. In the following section, we present a framework for the provision of ecosystem services by soil that addresses some of these limitations.

3. Proposed Framework for Soil Ecosystem Services

The conceptual framework for classifying, quantifying and modelling soil natural capital and ecosystem services (Fig. 2) provides a *broader and more holistic* approach than previous attempts to identify soil ecosystem services by linking soil ecosystem services to soil natural capital. It shows how external drivers impact on processes that underpin soil natural capital and ecosystem services and how soil ecosystem services contribute to human well-being. The framework consists of five main interconnected components: (1) soils as natural capital; (2) natural capital formation, maintenance and degradation; (3) the drivers of soil processes; (4) provisioning, regulating and cultural soil ecosystem services; and (5) human needs fulfilled by soil ecosystem services.

3.1. Soil Natural Capital

Soil natural capital is capital is defined here as a stock of natural assets yielding a flow of either natural resources or ecosystem services (Costanza and Daly, 1992). Since the flow of services from ecosystems requires that they function as whole systems, the structure, composition and diversity of the ecosystem are important components of natural capital. By incorporating the idea of soils as natural capital into the conceptual framework, we provide a more complete picture, as well as infuse soil science knowledge into the discussion. Doing so creates the opportunity to value the natural capital of soils and also to track the changes in these values for a given human use. The natural capital of soils can be characterised by soil properties. The idea of soil properties is central to soil science and it is the way in which soil scientists and agronomists describe and characterise soils. As measurable quantities, soil properties enable soil scientists to compare soils on different criteria. The concept of soil properties can be traced back to the 1840s when scientists studied the chemical properties of soils: first, soil's weak-acid properties and the capacity to absorb and exchange cations (Way, 1850) and anions, and later the colloidal properties of soil clays and their mineralogy (Schloesing, 1874). In parallel, soil physics was developed as a discipline about soil moisture and water physics, based on the work of Darcy (1803–1858) but also the principles and determination of the grain-size distribution in soils (i.e. clay, silt and sand fractions) that influences both physical and chemical properties. Understanding mechanical properties of soils came later (beginning of the 20th century) with rheology (study of deformation and flow of matter) informing us of the behaviour of soils under stress (Yaalon, 1997).

A soil property can refer to any soil component that can be measured and used to compare or assess soils. For instance, when soils contain stones, the properties related to stones can be size, percentage of stones in soil volume or percentage of stones in soil mass. Soil properties are routinely evaluated in terms of three broad dimensions — physical, chemical or biological. For example, texture is a physical soil property representing the relative proportion of sand, silt and clay in the soil. Texture is a determinant factor of aggregate size and soil structure and is also an indicator of other soil properties like water storage capacity and drainage class. Cation exchange capacity (CEC) is a chemical property. It is a quantitative measure of the soil's ability to hold cations, and indicates the quantity of negative charges present per unit mass of soil. CEC is influenced by the amount of organic matter (OM), the types and amounts of clays, and pH (Fig. 3). Microbial biomass and its activity are biological soil properties. It refers to the size and diversity of microbial populations associated with organic matter decomposition and nutrient transformations.

Soil properties are interrelated with each other and with soil components (Fig. 3). For example, physical properties influence soil moisture content and water movements, which then influence soil chemical and biological properties. In return, soil chemical and biological processes and properties influence physical properties by the production of precipitates and colloids for example. Properties influence the intensity at which the processes occur and are at the same time products of these processes. It is very important when quantifying and valuing the natural capital stocks of a soil that double counting of soil properties does not occur and there is a clear understanding of the influence soil properties have on soil processes and how they collectively contribute to ecosystem services.

Most of the modern soil classifications are based on the properties of horizons within the soil. Soil classification provides a framework that facilitates communication and understanding amongst pedologists, when there is a prior agreement on concepts. They also make information more accessible to non-specialists. The properties chosen to build-up classification schemes are those that can be observable or measured in the field or measured in the laboratory. Those linked directly to use are of particular interest. In the past, climate parameters were utilised in the classification of soils. The World Reference Base for Soil Resources (WRB) is the international standard taxonomic soil classification system endorsed by the International Union of Soil Sciences (IUSS), replacing the previous Food and Agriculture Organisation (FAO) soil classification. The WRB is inspired by modern soil classification concepts, including the United States Department of Agriculture (USDA) soil taxonomy, the legend for the FAO Soil Map of the World, the French Référentiel Pédologique, and Russian concepts. The WRB classification is based mainly on soil morphology as an expression of soil formation conditions. Soil classifications and associated properties alone cannot be used for compiling an inventory of soil natural capital stocks and their value. Human use (land use) or purpose must be added to soil classifications before a value can be assigned to the natural capital stocks by quantifying the ecosystem services they provide. For example, a deep stony soil will be suited for grape growing, average for sunflower cropping, and unsuitable for arable cropping because these different crops require different optimal water and drainage conditions. Land use is therefore a very important component of the relationship between soil natural capital stocks, ecosystem services and human welfare. Notwithstanding the difficulties and intricacies of applying soil classification schema to a "natural capital-ecosystem services" framework, the existence of soil classification systems does provide a rigorous way of considering soil's stocks, on which ecological economists and others concerned with managing soil ecosystem services can draw on as a basis for recognising differences between soils.

When describing soil natural capital stocks and the sustainable productive capability of soils, it is useful to make the distinction between inherent soil properties derived from soil formation conditions and those properties that respond to active management (Fig. 2). Lynn et al. (2009, p. 86), make the distinction between "permanent, removable and modifiable limitations". Robinson et al. (2009, p. 1906) made a similar distinction between "inherent and dynamic properties". In this paper, we make the distinction between *inherent* and *manageable* soil properties (Fig. 2). Inherent soil properties typically include slope, depth, cation exchange capacity, and clay types. They cannot readily be changed without significant modification of the soil, its environment, or without involving prohibitive costs. Manageable soil properties typically include soluble phosphate, mineral nitrogen, organic matter contents and macroporosity (Fig. 2). In an ecosystem services management framework, although recognising and taking account of inherent soil properties, the manageable properties assume more practical importance as they provide the opportunity for agronomists, farmers and other stakeholders to optimise the provision of ecosystem services from soils. Knowing what type of properties is involved in the processes and the services they support is therefore essential. For this reason, in putting forward the conceptual framework of soil natural capital and ecosystem services, we put major emphasis on recognising and distinguishing the differences between inherent and manageable soil properties within soil natural capital stocks. The ability to track changes in the inherent properties of soils provides a tool for both industry and policy to separate the effects of short-term management practices from the long-term changes in our soil resources.

A distinction also needs to be made between soil natural capital and added capital, with the latter associated with technologies employed to lift the productive capacity of soils (e.g. irrigation to overcome limited water holding capacity). For this reason, variations in the soil natural capital can lead to very marked differences in land use and farming systems and associated environmental footprint (Mackay, 2008).

3.2. Soil Natural Capital Formation, Maintenance and Degradation

Soil natural capital, like any type of capital (manufactured, social, human), is formed, maintained and degraded over time. The following section details the processes involved in these phenomena.

3.2.1. Soil Natural Capital Formation and Maintenance: Supporting Processes

Soils are complex dynamic systems consisting of soil components (abiotic and biotic) interconnected by biological, physical and chemical processes. Soil processes support soil formation, which is the development of soil properties and soil natural capital stocks. Soil processes also form the core of soil functioning and allow the establishment of equilibria and the maintenance of natural capital stocks (Fig. 2). What we call here "supporting processes" (Fig. 2) are, strictly speaking, categories of processes driving soil natural capital formation and soil functioning. We chose this denomination to relate to the Millennium Ecosystem Assessment framework (MEA, 2005) but we depart from the MEA by talking about supporting processes rather than services. The definitions of the terms given in this paper allow us to make that distinction since these processes do not directly affect human well-being.

The following supporting processes are included in the conceptual framework (Fig. 2):

- *Nutrient cycling*, which refers to the processes by which a chemical element moves through both the biotic and abiotic compartments of soils. Nutrient cycles are a way to conceptualise the transformations of elements in a soil. The transformation, or cycling, of nutrients into different forms in soils is what maintain equilibria between forms, e.g. soil solution concentrations of nitrate drive many processes such as plant uptake, exchange reactions with clay surfaces or microbial immobilisation.
- *Water cycling*, which refers to the physical processes enabling water to enter soils, be stored and released. Soil moisture is the driver of many chemical and biological processes and is therefore essential in soil development and functioning. The continuous movements of water through soils carrying nutrients disturb chemical equilibria, and thereby drive transformations.
- *Soil biological activity*: soils provide habitat to a great diversity of species, enabling them to function and develop. In return, the activity and diversity of soil biota are essential to soil structure, nutrient cycling, and detoxification. Biological processes include predation, excretion and primary production among others.

These processes are at the core of soil formation (pedogenesis), building up the physical, biological and chemical stocks of soils. Pedogenesis is the combined effect of physical, chemical, biological, and anthropogenic processes on soil parent material. Soils are formed from the rock materials that make up the earth's crust. Soils can be formed from the underlying bedrock, from material moved relatively small distances (e.g. down slope) or even considerable distances from where the bedrock was originally exposed to the environment. The formation of a soil in these mineral deposits is a complex process. It may take centuries for a developing soil to acquire distinct profile characteristics. Minerals derived from weathered rocks undergo chemical weathering creating secondary minerals and other compounds that vary in water solubility. These constituents are translocated through the soil profile by water and biota. In addition to chemical weathering, physical weathering also takes place. It refers to the disintegration of mineral matter into increasingly smaller fragments or particles. Pedogenic processes, driven by nutrients and water cycles and biological activity, include the accumulation of organic matter, leaching, the accumulation of soluble salts, calcium carbonate and colloids, nutrient redistribution, gleying and the deposition and loss of materials by erosion, and are very important in soil development and defining soil properties.

Five factors control soil development and natural capital formation: parent material, climate, vegetation, topography, and time (Jenny, 1941). The mineralogy of the parent material influences weathering products and the mineral composition of the soil. Rainfall influences the intensity of weathering and the leaching of weathering products, while temperature will change the speed of chemical and biological reactions. Some indirect climatic effects are through biomass production and rates of organic material decomposition. Species of flora and fauna have a significant effect on the type of soil formed but in time the distribution of flora and fauna depends on climate, topography, and parent material. Landscape relief affects soil formation in different ways, including soil depth, modification of local climate, and available water.

Thus, we saw how, with time, supporting processes gradually build up and create soil properties and ensure the maintenance of the dynamic equilibria underpinning soil natural capital. However, soil natural capital is also degraded over time.

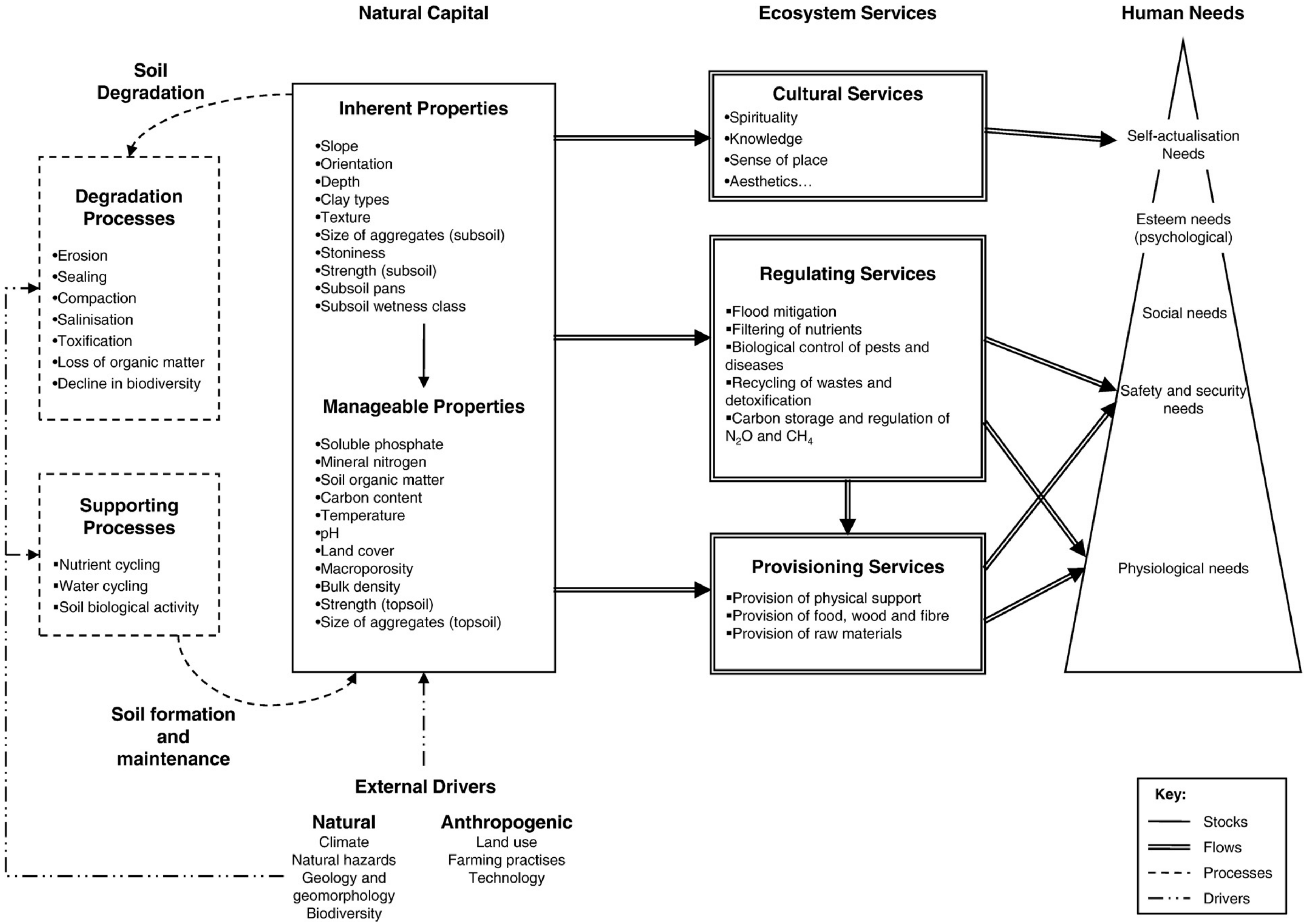

Fig. 2. Framework for the provision of ecosystem services from soil natural capital.

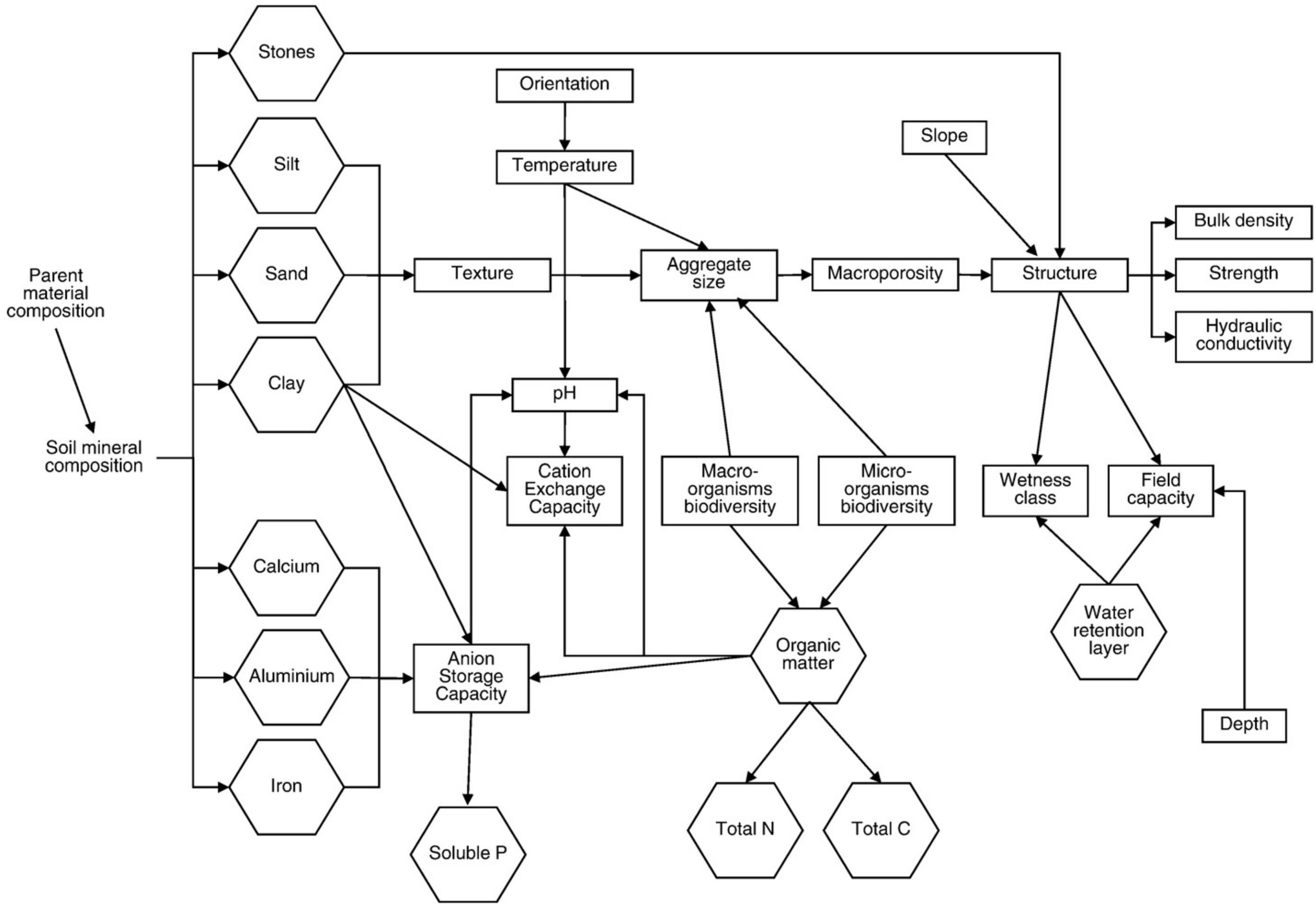

Fig. 3. Simplified relationships between some soil components (hexagons) and properties (rectangles).

3.2.2. Soil Natural Capital Degradation: Degradation Processes

The MEA (2005) brought to attention the degradation and loss of ecosystems, but there has been very little recognition of degradation processes in the soil ecosystem services literature (Palm et al., 2007). However, the idea of ecosystem "dis-services" has begun to emerge (Swinton et al., 2007). The notion of dis-service refers to an adverse change in a stock or in a process leading to a loss of ecosystem services. There is a real need to consider the degradation of soil natural capital, and the degradation of natural capital stocks in general, and to identify and quantify the processes behind this degradation because losing natural capital stocks means losing ecosystem services. By limiting soil natural capital degradation, we can act on ecosystem services provision.

Soils can be qualitatively (e.g. salinisation) and quantitatively (e.g. erosion) degraded over time. Again, this is analogous and conceptually the same as the degradation (or depreciation) of manufactured capital used in national economic accounts and macro-economics. There are a number of types of soil degradation processes: physical, chemical and biological. Physical degradation processes refer to the structural breakdown of the soil through aggregates disruption. This results in the loss of pore function, which leads to a reduction in surface infiltration, increased water run-off and decreased drainage, in time leading to a decrease in gases availability to plants and biota. Physical degradation processes include (Fig. 2):

- *Erosion*: the loss of soil material. Soil particles from disrupted soil aggregates or even soil horizons are removed from site by gravity, water, ice or wind. Erosion causes the loss of soil profile, which impacts on soil depth and therefore on the levels of stocks of nutrients and organic matter, for example.
- *Sealing and crusting*: the formation of a structural seal at the soil surface that crusts once dry. The impact of raindrops causes physical disintegration of surface aggregates. The physico-chemical dispersion of clay particles into pores results in decreased porosity and infiltration. Surface sealing and crusting also prevent seedling emergence.
- *Compaction*: loss of soil structure leading to lower infiltration decreased drainage and increased surface run-off. It also reduces the movements of soil gases (O_2, CO_2). Farming practices including high cattle stocking rates or tillage destroy soil aggregates and can lead to the formation of a compacted layer at depth.

Chemical degradation refers to the processes leading to soil chemical imbalances. Main chemical degradation processes include (Fig. 2):

- *Salinisation*: the accumulation of salts like sodium or magnesium chloride. It lowers the water potential, making water harder to take up by plants. Salt crystals can also destroy roots and breakdown soil aggregates.
- *Loss of nutrients* by leaching and run-off. It decreases the levels of macronutrients on exchange sites (clays, OM) and in soil solution.
- *Acidification*: it occurs when cations are excessively leached from soils, when the application of fertilisers is not balanced or when mineralisation is too intense because of soil structure perturbation.
- *Toxification*: the excessive build-up of some elements (e.g. aluminium, iron) and heavy metals (e.g. mercury, chromium, lead). It can be caused by excessive weathering or industrial activities.

Biological degradation processes can also degrade the natural capital of soils. The artificial disruption of soil structure (tillage, cattle

Table 2
Soil ecosystem services and agro-ecosystem services classifications and the concordances between them.

Reference	Type of framework	Services attributable to soils									
		Nutrients					Water			Structure	
		Provision to plants	Contribution to plant production	Renewal through soil formation	Cycles regulation	Movements	Provision to plants	Filtering	Flood control	Support provision	Erosion control
Daily (1997)	Soil specific	Retention and delivery of nutrients to plants	NC	Renewal of soil fertility	Regulation of major element cycles	NC	NC	NC	Buffering and moderation of the hydrological cycle	Physical support of plants	NC
Wall et al. (2004)	Soil specific	Retention and delivery of nutrients to plants	Contribution to plant production for food, fuel and fibber	Generation and renewal of soil and sediment structure and soil fertility	Regulation of major biogeochemical cycles	Translocation of nutrients, particles and gases	NC	Provision of clean drinking water	Mitigation of floods and droughts	Contribution to landscape heterogeneity and stability	Erosion control
Lavelle et al. (2006)	Soil specific	NC	Enhancement of primary production	Soil formation	Nutrient cycling	NC	Water supply	NC	Flood control	NC	Erosion control
Barrios (2007)	Soil specific	Nutrient uptake	NC	NC	Nutrient cycling	NC	Water flow	NC	Storage of water	NC	Regulation of soil erosion
Weber (2007)	Soil specific	NC	Production function	NC	Reactor function	NC	NC	Filter function	Buffer function	Carrier function	NC
Swinton et al. (2007)	Agro-ecosystems	NC	Food, fibre	NC	NC	NC	NC	Water pollution	NC	NC	NC
Zhang et al. (2007)	Agro-ecosystems	NC	Food, fibre production	Soil formation	Nutrient cycling	NC	Water provision	Water purification	NC	NC	Soil retention
Sandhu et al. (2008)	Agro-ecosystems	Soil fertility	Food	Soil formation	Mineralisation of plants nutrients	NC	Hydrological flows	NC	NC	NC	NC
Porter et al. (2009)	Agro-ecosystems	NC	Food production	Soil formation	N regulation	NC	Hydrological flow	NC	NC	NC	NC

Reference	Services attributable to soils							General agro-ecosystems' services			
	Climate regulation			Biodiversity			Resources	Pollination	Culture		
	General	Carbon sequestration	GHGs production	General habitat	Populations regulation	Recycling actions			General	Recreation	Aesthetics
Daily (1997)	NC	NC	NC	NC	NC	Disposal of wastes and dead OM	NC	NC	NC	NC	NC
Wall et al. (2004)	Modification of anthropogenically driven global change	NC	Regulation of atmospheric trace gases	Vital component of habitats important for recreation and natural history	Control of potential pests and pathogens	Bioremediation of wastes and pollutants	NC	NC	NC	NC	NC
Lavelle et al. (2006)	Climate regulation	NC	NC	NC	Regulation of animal and plant populations	NC	NC	NC	NC	NC	NC
Barrios (2007)	NC	Carbon sequestration	NC	NC	Biological control of pests and diseases	NC	NC	NC	NC	NC	NC
Weber (2007)	Climate regulating function		NC	Habitat function	NC	NC	Resource function	NC	Cultural and historical function	NC	NC
Swinton et al. (2007)	NC	Carbon sequestration	NC	Biodiversity conservation	NC	Odours Health risks	NC	NC	NC	Recreation	Aesthetics
Zhang et al. (2007)	Climate regulation	NC	NC	Genetic diversity	Pest control	NC	NC	Pollination	NC	NC	Aesthetic landscapes
Sandhu et al. (2008)	NC	Carbon accumulation	NC	NC	Biological control of pests	NC	Raw materials	Pollination	NC	NC	Aesthetics
Porter et al. (2009)	NC	Carbon accumulation	NC	NC	Biological control of pests	NC	Raw material production	Pollination	NC	NC	Aesthetics

NC: not considered.

treading) can lead to excessive activity of the soil biota due to oxygenation and therefore excessive mineralisation of organic matter leading to the loss of structure and nutrients.

All the processes mentioned above add to, maintain or degrade soil natural capital. One needs to acknowledge that they can be influenced by a number of drivers, natural and anthropogenic.

3.3. External Drivers

Soil processes are influenced by many drivers more or less external to the system where the processes take place. These drivers can come from natural origins or be anthropogenic, influencing soil processes in different ways, including the nature and speed of the processes. The drivers impacting on the inputs to, or outputs of, a system will influence the type of reactions taking place. By influencing soil processes, external drivers will therefore also impact on the levels and nature of soil natural capital stocks (Fig. 2). Natural drivers influencing soil processes and natural capital stocks include climate, natural hazards, geology and geomorphology and biodiversity (Fig. 2). Climate has a very significant impact on soil processes and therefore on the provision of ecosystem services from soils. The characteristics of local climate (rainfall intensity, temperature, sunshine) influence supporting processes, degradation processes and biodiversity by driving soil moisture and temperature. Anthropogenically driven climate change therefore impacts on both soil natural capital stocks and ecosystem services. Natural hazards, like earthquakes or volcanic eruptions for example, can change a soil's environment (e.g. bury it or compromise the integrity of soil structure at different scales), thereby modifying supporting and degradation processes like water cycling or erosion. The geological origin of the parent material determines the initial minerals in soils that will drive soil development and properties. Geological history, as well as the climate of the area, determines the morphology of landscapes, therefore the undergoing intensity of degradation and supporting processes. Biodiversity is the agent of biological reactions; therefore the type and variety of species present in an area will influence the type and intensity of the biological processes.

Anthropogenic drivers, such as land use, farming practices and technologies, also influence soil processes (Fig. 2). The type of land use (e.g. cropping, livestock) determines the type of disturbance (e.g. tillage, treading, use of agrochemicals) as well as inputs (e.g. excrements, synthetic fertilisers) applied to the soil. Farming practices determine the level of intensity of the disturbances (e.g. organic versus conventional cropping) and the amount of inputs to the soil (e.g. quantity and timing of fertilisation). The evolution of technology provides humans with more tools to manage soil processes and the impacts of the pressures applied to the environment, for example, the use of nitrification inhibitors can reduce nitrate leaching losses and nitrous oxide emissions from soils. Soil scientists have been studying the impacts of many of these drivers on soil processes and properties for many years and some areas like the impacts of farming practices and climate on soil properties, are therefore well understood and documented.

We saw that soil natural capital stocks can be characterised by soil properties, that the formation, maintenance and degradation of these stocks are determined by soil processes and that soil processes can be influenced by external drivers. By showing how soil properties and processes link to soil natural capital, the large body of knowledge on soil processes from the soil science literature can be included into the framework for the provision of ecosystem services from soils. In the following section, we detail soil ecosystem services.

3.4. Provisioning, Regulating and Cultural Ecosystem Services from Soils

Ecosystem services are defined here as the beneficial flows arising from natural capital stocks and fulfilling human needs. Soils take part in the provision of a number of ecosystem services that we identified by talking with soil scientists and compiling the literature (Table 2). We chose to classify these soil services according to the MEA (2005) model, so the reader can relate to more general ecosystem service frameworks. Soils provide three types of services: provisioning, regulating and cultural services. Provisioning services are defined as "the products obtained from ecosystems" (MEA, 2005, p. 40). Soils specifically provide a number of products useful for humans:

- *The provision of food, wood and fibre*: Humans use a great variety of plants for a diversity of purposes (food, building, energy, fibre, medicines). By enabling plants to grow, soils provide a service to humans. Soils physically support plants and also supply them with nutrients and water. The natural capital stocks insuring the provision of the service are embodied by soil structure, water holding capacity and nutrients fertility.
- *The provision of physical support*: soils form the surface of the earth and represent the physical base on which animals, humans and infrastructures stand. Even an otherwise unproductive soil may provide physical support to human infrastructures (e.g. stretches of the Trans-Australia Railway across the Nullarbor Desert). Soils also provide support to animal species that benefit humans (e.g. livestock). The strength, intactness and resilience of soil structure represent the natural capital stocks behind this service.
- *The provision of raw materials*: soils can be source of raw materials like, for example, peat for fuel and clay for potting. These materials stocks are the source of the service. However, renewability of these stocks is questionable (de Groot et al., 2002).

Soils also provide regulating services which enable humans to live in a stable, healthy and resilient environment. The regulation that these services provide come from soil processes and their effect on the establishment of equilibria between natural capital stocks. Soil regulating services included in our framework are (Fig. 2):

- *Flood mitigation*: soils have the capacity to store and retain quantities of water and therefore can mitigate and lessen the impacts of extreme climatic events and limit flooding. Soil structure and more precisely macroporosity, as well as processes like infiltration and drainage will impact on this service.
- *Filtering of nutrients*: if the solutes present in soil (e.g. nitrates, phosphates) are leached, they can become a contaminant in aquatic ecosystems (e.g. eutrophication) and a threat to human health (e.g. nitrate in drinking water). Soils have the ability to absorb and retain solutes, therefore avoiding their release into water. Natural capital stocks of clays and OM, as well as processes like adsorption and precipitation regulate this service and therefore drive the quality of run-off and drainage waters and wider water bodies such as ground water, lakes and rivers.
- *Biological control of pests and diseases*: by providing habitat to beneficial species, soils can support plant growth (rhizobium, mycorrhizae) and control the proliferation of pests (crops, animals or humans pests) and harmful disease vectors (e.g. viruses, bacteria). Soil conditions (e.g. moisture, temperature) determine the quality of the soil habitat and thereby select the type of organisms present. This service depends on soil properties and the biological processes driving inter- and intra-specific interactions (symbiosis, competition).
- *Recycling of wastes and detoxification*: soils can self-detoxify and recycle wastes. Soil biota degrades and decomposes dead organic matter into more simple forms that organisms can reuse. Soils can also absorb (physically) or destroy chemical compounds that can be harmful to humans, or organisms useful to humans. This service depends on biological processes like mineralisation and immobilisation and therefore is also related to the natural capital stocks of nutrients available for soil biota or for chemical reactions.
- *Carbon storage and regulation of N_2O and CH_4 emissions*: soils play an important role in regulating many atmospheric constituents,

therefore impacting on air quality. Perhaps most important is the ability of soils to store carbon as stable organic matter which is a non-negligible benefit when talking about off-setting greenhouse gases emissions. This service is mainly based on OM stocks and the processes driving them but also on soils conditions (e.g. moisture and temperature) which regulate soil biota activity and thereby the production of greenhouse gases like nitrous oxide (N_2O) and methane (CH_4).

Soil provisioning and regulating services arise at very different scales ranging from microns (habit for micro-organisms) to landscape (flood mitigation) to the globe (air quality).

Notably, none of the previous studies (Barrios, 2007; Daily et al., 1997; Lavelle et al., 2006; Wall et al., 2004; Weber, 2007) on soil ecosystem services cover or identify “cultural services” (Table 2). This is a curious omission as soils alone, as part of landscapes that support vegetation, have across many cultures been a source of aesthetic experiences, spiritual enrichment, and recreation. Many deities and religious beliefs refer specifically to the earth and its sacredness and soils also have various cultural uses across the globe from being a place to bury the dead, a material to build houses or a place to store and cook food (Māori hāngi). The point here is not to detail all the cultural services provided by soils but to acknowledge that these services, even if almost always forgotten, are of tremendous consequence.

We have examined services provided by soils and acknowledge that they can be of a different nature, but to complete our framework, in the following section we need to look at human needs and how ecosystem services fulfil them.

3.5. Human Needs Fulfilled by Soil Ecosystem Services

Ecosystem services exist because they meet a human need. This is the very essence of the anthropocentric concept of ecosystem services. However, few studies in the ecosystem services literature go as far as specifying how and what human needs are potentially or actually fulfilled by ecosystem services. One very notable exception is the Millennium Ecosystem Assessment (2005), which, although not explicitly acknowledging it, shows how ecosystem services contribute to human well-being by using a framework that resembles Maslow's “Hierarchy of needs” (1943). Maslow's (1943) classic study of the so-called “Hierarchy of needs” is the foundation study in this domain. This hierarchy has five levels: the first four levels are deficiency needs: physiological needs, safety and security needs, social (love and belonging) needs, and esteem (psychological) needs; the last level is self-actualisation needs. Deficiency needs must be met first, the individual prioritises them; the higher needs can be considered only when the lower needs are met. Maslow's framework has been widely criticised (Wahba and Bridwell, 1976) on a number of grounds. Probably the most persistent critique is that Maslow's framework is based on a hierarchal structure for which there is a lack of strong evidence. For example, a starving artist may be self-actualised while his/her physiological needs (e.g. food) may be inadequately fulfilled. In this context, Chilean economist Manfred Max-Neef's “matrix of needs” (1992) is perhaps a better reflection of reality. In this framework many needs are complementary and different needs can be fulfilled simultaneously. Max-Neef classifies fundamental “axiological categories” – subsistence, protection, affection, understanding, participation, idleness, creation, identity, and freedom – that are split into four “existential categories” (being, having, doing and interacting), thereby forming a matrix of needs. Ecological economist Herman Daly somewhat bravely presents an even broader contextualisation of human needs, in terms of his “end-means” spectrum (Daly and Farley, 2003). This spectrum links ultimate ends (final cause and “God”) to intermediate ends (health, safety, comfort) to ultimate means (material cause, low entropy matter energy). However, whatever philosophical construct of human needs is selected, it is inevitably a poor representation of the complexity, subtlety or ever-changing nature of human needs.

Even though Maslow's hierarchy of needs (1943) is an overly simplistic picture, it's easy to comprehend and thereby enables us to point out that ecosystem services relate to human needs on two different levels. First, at the physical level, provisioning services provide goods useful for the fulfilment of some physiological needs: food, fibre for clothing, sources of energy, and support for infrastructures (Fig. 2). Regulating services also fulfil some physiological needs like clean air and clean water by regulating greenhouse gases emissions and filtering water. Moreover, provisioning and regulating services also fulfil safety and security needs by ensuring the stability of human habitat through soil structure stability, flood mitigation, the control of pests and the recycling of wastes (Fig. 2). Second, at the non-physical level, ecosystems provide aesthetics, spiritual and cultural benefits through cultural services, thereby fulfilling self-actualisation needs. Again, the fulfilment relationships between services and human needs are not a one-to-one correspondence.

As shown in Fig. 2, it should also be noted that some needs in Maslow's hierarchy (1943) (social and esteem needs) cannot be fulfilled by ecosystem services. This is because these needs are only based on our own self-perception of emotionally-based relationships with other human beings (or even animals).

4. Conclusion

This paper draws on soil science and builds on the current thinking on ecosystem services to develop a framework for classifying and quantifying the natural capital and ecosystem services of soils. The framework shows how soil natural capital stocks can be characterised by soil properties and how the provision of ecosystem services from soils is linked to both manageable and inherent soil properties. We argue supporting processes ensure the formation and maintenance of soil natural capital and that degradation processes drive natural capital depletion. These processes are influenced by both natural and anthropogenic drivers. Including this scientific knowledge in the framework opens the soil black-box and creates the opportunity to value the natural capital of soils and also to track the changes in these values for a given human use. It also allows, for the first time, the inclusion of differences between soils into broader ecosystem service frameworks.

The framework presented here is implemented in an on-going study to quantify and value ecosystem services from soils at the farm level. The framework concepts are used to incorporate the vast scientific modern-day understanding of soil processes and taxonomy into a model using pedotransfer functions to link the soil biophysical processes and properties at the origin of the provision of each soil ecosystem service to a biophysical measure of each service. The model is then able to show how soil natural capital, farming practices and soil management impact on the provision of ecosystem services.

Such a model paired with an economic valuation of soil services provides a very powerful management tool for economists and policy makers to better understand the provision of ecosystem services from soils and weigh more carefully soil natural capital and soil services values in rural development processes.

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