Geoderma 213 (2014) 203–213

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

The dimensions of soil security

Alex McBratney [a], Damien J. Field [a,*], Andrea Koch [b]

[a] Department of Environmental Sciences, Faculty of Agriculture and Environment, The University of Sydney, New South Wales, Australia
[b] Soil Carbon Initiative, United States Studies Centre, The University of Sydney, New South Wales, Australia

ARTICLE INFO

Article history:
Received 26 May 2013
Received in revised form 9 August 2013
Accepted 12 August 2013
Available online 12 September 2013

Keywords:
Food security
Water security
Ecosystem services
Natural capital
Soil health
Soil protection

ABSTRACT

Soil security, an overarching concept of soil motivated by sustainable development, is concerned with the maintenance and improvement of the global soil resource to produce food, fibre and fresh water, contribute to energy and climate sustainability, and to maintain the biodiversity and the overall protection of the ecosystem. Security is used here for soil in the same sense that it is used widely for food and water. It is argued that soil has an integral part to play in the global environmental sustainability challenges of food security, water security, energy sustainability, climate stability, biodiversity, and ecosystem service delivery. Indeed, soil has the same existential status as these issues and should be recognized and highlighted similarly. The concept of soil security is multidimensional. It acknowledges the five dimensions of (1) capability, (2) condition, (3) capital, (4) connectivity and (5) codification, of soil entities which encompass the social, economic and biophysical sciences and recognize policy and legal frameworks. The soil security concept is compared with the cognate, but more limited, notions of soil quality, health and protection.

1. Introduction

A number of large existential environmental challenges have been recognized for the sustainable development of humanity and planet Earth. These are Food Security, Water Security, Energy Security, Climate Change Abatement, Biodiversity Protection and Ecosystem Service Delivery (Bouma and McBratney, 2013). They all have similar characteristics; namely, they are global, they are complex and difficult to resolve, and they are inter-related. They all are addressed using a combination of dimensions with a focus on servicing mankind. The need to provide food and have water available to support the predicted world's population of over nine billion (Godfray et al., 2010) requires the provision of enough that is of good quality and is readily available. The provision of reliable and affordable energy while minimizing the impact on climate will depend on continued energy supply and its alternatives that do not result in increased greenhouse gas emissions (Janzen et al., 2011). These pursuits will all impact on ecosystem services and present a continuing challenge to preserve the global biodiversity.

When one analyses these environmental challenges we can recognize that soil has a part to play in all of these (Herrick, 2000), yet many exploratory models that are used to investigate these global challenges at best incorporate limited soil expertise (Bouma and McBratney, 2013). Indeed it can be said that soil underpins these and the degradation of the soil resource may have grave impacts. It has been reported that there is currently a decline in soil functions, listed in Fig. 1, which will affect its ability to provide ecosystem services and goods (Lal, 2010a). Soil degradation such as, erosion, fertility loss, salinity, acidification, soil carbon decline, and compaction have long been reported and are recognized as threats by the European Union (CEC, 2006). These have detrimental consequences for agricultural productivity, provision of water, increased greenhouse gases and loss of biodiversity (Koch et al., 2013). Without secure soil we cannot be sure of secure supplies of food and fibre, of clean fresh water, or of diversity in the landscape. We also reduce the potential of soil to act as a sink in the carbon cycle, and we remove a core platform for the production of renewable energy sources.

Because of this the security of soil in itself should be promoted to the status of a global existential challenge (Koch et al., in press). To do so we can define Soil Security as in McBratney et al. (2012) as being concerned with the maintenance and improvement of the world's soil resource to produce food, fibre and freshwater, contribute to energy and climate sustainability, and maintain the biodiversity and the overall protection of the ecosystem. In this definition, security is used in the same sense that it is used for food, water and energy. To frame this concept a set of dimensions need to be established and defined and, as with other concepts such as food and water security, these dimensions should account for the quantity, quality and accessibility of the soil. It is also essential to recognize that this concept is not being developed in vacuo and that similar concepts of soil quality, soil health and soil protection have also been proposed to address the need to maintain and manage

---

* Corresponding author at: Department of Environmental Sciences, The University of Sydney, Suite 103, Biomedical Building, 1 Central Ave, Eveleigh, New South Wales, Australia. Tel.: +61 2 8627 1138; fax: +61 2 8627 1099.
E-mail address: damien.field@sydney.edu.au (D.J. Field).

0016-7061
http://dx.doi.org/10.1016/j.geoderma.2013.08.013

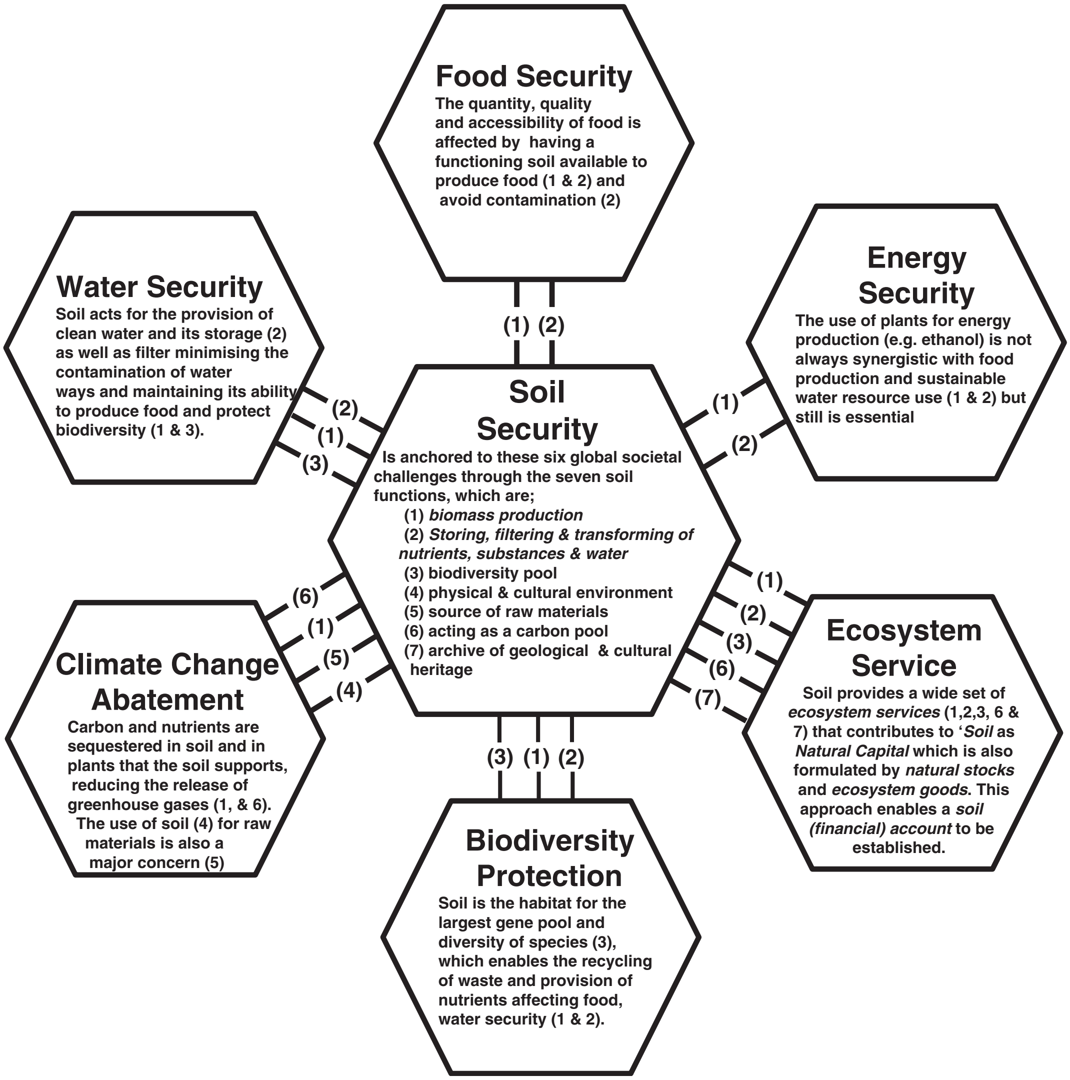

Fig. 1. Aligning the established scientific concept of soil functions (CEC, 2006) as listed under *Soil Security* in order (read left to right, or top to bottom) of their relative immediate impact for each of the major societal challenges.

the condition of the soil (Doran and Ziess, 2000; Karlen et al., 2001; Bouma and Droogers, 2007).

So we think that a sustainable development concept for soil termed *soil security* similar in scope to those above is worthy of investigation and development. The aim of this paper is to develop this concept further.

2. Characteristics of the six global existential environmental challenges

Various communities have investigated the six previously recognized global existential environmental challenges. Various characteristics or dimensions of each have been recognized for their description, assessment and eventual amelioration. It is instructive to examine these with a view to revealing a set of characteristics or dimensions for delineating, evaluating and facilitating soil security.

2.1. Food security

The projected need to feed 9 billion people by 2050 can partly be met by closing the yield gap and increasing the production limits of agriculture (Godfray et al., 2010). Access to good quality soil combined with soil conservation, the knowledge for best management and adoption of technologies (Fedoroff et al., 2010) should contribute to maximizing the yield potential (Pretty et al., 2011). The growing challenge of not being able to identify sources of soil amendments, e.g. phosphorus used to maintain or improve fertility is increasing (Cordell et al., 2009).

Food security is built on three pillars of *availability*, *access* and *use*. Essentially, food availability is referring to having sufficient quantity and a reliable source of food supply, and access focuses on having the resources to obtain high quality and nutritious food (Pinstrup-Anderson, 2009; Godfray et al., 2010). Food use describes having the knowledge of basic nutrition, as well as access to non-food inputs of adequate water and sanitation or lack of contamination (World Health Organization, 2012). These concerns have stimulated efforts to ensure food security by improving yield and quality, minimizing loss of productivity by land degradation, pollution, and urbanization, as well as, the need for water supply and storage (Chen, 2007; Godfray et al., 2010).

As illustrated in Fig. (1) the functions soil provides in this domain are biomass production along with its ability for filtering, storing and transforming of nutrients, substances and water (Lal, 2010b; Scherr, 1999; Stocking, 2003).

2.2. Water security

Water shortages are an immediate threat (Anonymous, 2008). The opportunity to harvest water from rivers and dams, labelled as 'blue water', is becoming limiting in regions around the globe and there are now efforts to understand the flux of transpired water and its return from the atmosphere (Falkenmark and Rockström, 2006). Evidence has been produced demonstrating that minimizing soil disturbance (e.g. minimum till) can conserve water (Hatfield et al., 2001) and research is continuing to understand the plant soil–water interactions, identified as 'green water', to improve the water use efficiency (Morison et al., 2008; Rockström et al., 2009).

The prevailing three pillars of *water security* have been strongly influenced by its interrelationship with food security (UNDESA, 2012). Water *quality* is concerned with the physical and chemical properties making water acceptable for use and water *scarcity* recognizes the natural and engineered availability of water and efforts to remove contaminants. The issue of water *cooperation* with its focus on management amongst stakeholders and its allocation and trade is the third pillar. There needs to be a quantity and quality of water to meet societal and ecosystem physical needs (Falkenmark, 2001).

The soil functions of water retention, filtering and transforming compounds and nutrient cycling (Fig. 1) are significant contributors to the provision of water for human, biomass production and ecosystem needs.

2.3. Energy security

Energy security is mainly concerned with understanding energy *availability* and *affordability* (Vera and Langlois, 2007). The availability is defined by having a (self-)sufficient and uninterrupted and diverse supply (Sovacool, 2007). Affordability is predicated upon having equitable access to affordable energy and the United Nations has recognized this using an 'energy ladder' account for different sources from electricity as the highest rung, through modern fuels (e.g. petroleum, natural gas, ethanol) down to traditional fuels (e.g. wood, charcoal, crop residues) (Legros et al., 2009).

Sovacool and Brown (2010) noted that up to 80% of the literature on energy security addressed availability and affordability, about one third of the literature addresses *economic efficiency* and one quarter *environmental sustainability*. The economic efficiency considers improved technologies that enhance the quality and delivery of energy (Gallagher et al., 2012) and the sustainability is concerned with ensuring that energy extraction does not exceed its regeneration, that emissions do not exceed assimilation capacities, and that non-renewable are depleted at rates equal to the discovery of renewable sources (Daly, 1979).

Of greater concern for soil is that the effect of competitive uses to produce energy such as crops for biofuels in addition to food production (Fig. 1) will demand from the soil resource (Tilman et al., 2009).

2.4. Climate-change abatement

The increased use of fossil fuels and land use change has been attributed to the potential for global climate change (Canadell et al., 2007). Janzen et al. (2011) has reported that increased CO_2 may affect photosynthetic rate, accelerate organic matter decay, alter precipitation patterns resulting in droughts, flooding or erosion, and shifting in arable lands resulting in changes in soil cultivation. The ability of the soil to sequester carbon has some potential to mitigate increases in atmospheric greenhouse gases. This is driven by the fact that there is more carbon stored in the world's soil than in the atmosphere (Davidson and Janssens, 2006) and the liberation of this carbon will contribute significantly to global warming (Lal, 2004).

According to Lal (2010b), managing the soil functions (Fig. 1) that affect the potential for carbon sequestration could not only mitigate the climate change, but also have positive impacts on agronomic productivity and the global food security.

2.5. Biodiversity protection

The Convention on Biological Diversity (1992) has three main goals, being: to conserve biological diversity, maintain sustainable use of its components, and a fair and equitable trade of benefits provided by genetic resources. There is strong focus on dimensions of *diversity within species*, *between species* and *of the ecosystem* and a number of global indicators are being proposed and accepted to assess biological diversity (Balmford et al., 2005; Luck et al., 2003).

'Soil biodiversity can be defined as the variation on soil life, from genes to communities, and the variations in soil habitats, from micro-aggregates to entire landscapes' (Turbé et al., 2010). The soil is the habitat for the largest gene pool and diversity of species and these organisms participate actively in soil processes that affect its formation and function (Lavelle et al., 2006). This is because soil micro-organisms contribute to the maintenance of the matter and energy transfer in terrestrial environments (Filip, 2002). In particular, biodiversity contributes to nutrient and water efficiencies, improves soil structure and protects against soil-borne diseases (Brussaard et al., 2007). To enable biodiversity protection to contribute to ecosystem formation and function outside of conservation areas, Swift et al. (2004) claim the promotion of land-use diversity at the landscape and farm scale should be a primary aim. There is a continuing need to deepen our understanding of the interactions between the biology–soil–plant–water (Fig. 1) systems and improve our ability to assess with reference to space and time to inform ecological risk assessment (Barrios, 2007; Ekschmitt and Griffiths, 1998; Ekschmitt et al., 2003; Mulder, 2006). This will inform land users and improve capabilities to predict adoption to environmental change and support good policy frameworks.

2.6. Ecosystem services

The term ecosystem service emerged in the early 1980s (Mooney and Ehrilch, 1997) and the provision of *ecosystem services* has received considerable attention and can be defined as '*the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly*' (De Groot, 1992). Since then a number of classifications have been developed to categorise ecosystem services (Robinson et al., 2012), and the recently framed Millennium Ecosystem Assessment (MEA, 2005) agrees with Noël and O'Connor (1998), Daily (1999) and Ekins et al. (2003a) describing four categories being: *supporting*, *provisioning*, *regulating* and *cultural* services (Table 1).

For soil the supporting service is generally concerned with providing support for plants, delivery of plant nutrients, and a gene pool. The major element and hydrological cycles, and disposal of waste are embraced as regulating services. Its excavation for building materials is an example of a provisioning service, while the spiritual value, archaeological preservation and heritage are cultural (Robinson et al., 2009). These four categories may themselves be regarded as the dimensions of ecosystem services. There have been a number of efforts by soil scientists to determine how soil science engages with these categories (Palm et al., 2007) which can be summarized using five of the seven functions of the soil that provide ecosystem goods or services (Fig. 1), and these would form part of a soil account (Boyd and Banzhaf, 2007). This account of soil needs to be broader than the performance indicators of soil health and quality to include the contribution soil makes to ecosystem services, consideration of the soil's natural capital and be able to articulate changes in soil so as to inform the policy making process (Dominati et al., 2010; Robinson et al., 2012).

Table 1
'Ecosystem services' of soil refers to the fundamental necessities to support life-encompassing human culture and its pursuits (based on Robinson et al., 2009).

Type of service	Economic value
Supporting	
Physical stability and supporting for plants	?
Renewal, retention and delivery of nutrients for plants	Production (yield) functions for applied nutrients
Habitat and gene pool	Biodiversity, new cultivars, sources of novel genes
Regulating	
Regulating of major elemental cycles	*Carbon, nitrogen*
Buffering, filtering and moderation of the hydrological cycle	Value of freshwater processed per hectare, flood attenuation
Disposal of wastes and dead organic matter	Nutrient cycling
Provisioning	
Building materials	Cost of materials, transport and storage
Cultural	
Heritage sites, archeological preserver of artefacts	?

3. Dimensions of soil security

A summary of the characteristics of global existential environmental challenges is that as well as having biophysical attributes, they also inevitably have economic, social and policy aspects. In a concept of soil for sustainable development all of these dimensions should be addressed simultaneously.

There has been a long history of soil evaluation or 'assessment frameworks' developed from Land Evaluation to Soil Quality assessments (McBratney et al., 2012). These soil-science-led assessments primarily have been developed to measure the inherent and manageable properties of the soil, which are taken as indicators of the soil's ability to function or provide a service using soil science dimensions (Robinson et al., 2012). These assessments are also relative, being affected by decisions that are value driven and contextual (Alrøe and Kristensen, 2002; Bouma et al., 2012; Schjønning et al., 2004) including: land management, economic, social and political/regulatory dimensions. This would require a multi-dimensional, multi-disciplinary approach recognizing all stakeholders, and therefore, a framework is required with dimensions that explicitly distinguish the assessment of the optimal state of the soil and the current state of the soil and, how the soil is effectively utilized. Such a distinction will enable a clearer comparison of the current condition of the system relative to its capability and an account of the values and context affecting how the soil system is being utilized in order to reconcile the measures using scientific principles and relativism.

For soil, its *capability* can be thought in terms of a reference state that defines an optimal capacity of the soil to which the current *condition* of the soil can be compared. There has been a long history of evaluating the capability of a soil, which involves correlating biomass production with a soil's intrinsic properties developed over pedological time periods (McBratney et al., 2012) and is quite often used in land-use planning. Since the early 1970s there has been recognition of an increasing number of soil functions, beyond just food and fibre production (e.g. water storage and filtering, waste management, biodiversity store), resulting in an ability to compare the relative changes in the soil condition (e.g. soil quality) within a land management timeframe (Warkentin and Fletcher, 1977). To determine if a soil is 'good' or 'bad' for a particular purpose (Carter et al., 1997) or if its use enhances or degrades its condition will depend on what value society places on this soil, who influences how it is used, and how this use may be regulated (Doran, 2002; Patzel et al., 2000). To account for this value-laden relative criteria we suggest that three dimensions identified as *capital*, *connectivity*, and *codification* be defined. We can refer to capability, condition, capital, connectivity and codification as the five 'Cs' that need to be assessed in order to secure a soil, i.e. the dimensions for a soil security framework.

3.1. Dimension 1: Capability

The capability of any given soil refers to its potential functionality and historically came out of work on agricultural development and land use, but it can be applied more widely. The question that capability can answer is, 'What functions can this soil be expected to perform, and in doing so what can it produce?' To answer this question it is equally important to understand the soil's capability in the context of its own reference state.

This dimension is strongly influenced by a long history of work by soil scientists on land evaluation (FAO, 1976) dating back to the 1920s, and it recognizes the intrinsic difference between different kinds of soil. A series of guidelines were produced by the FAO for land evaluation in dryland agriculture, forestry, irrigated agriculture, grazing and steeplands (FAO, 1983, 1984, 1985, 1991; Siderius, 1986). This land evaluation framework improved interpretations of soil by providing land suitability classes, and just as importantly, determined specific well-defined land qualities on which these suitabilities are based (Bouma, 1989; Bouma et al., 2012). The idea of land qualities is broader than the concept of soil qualities and recognizes that "the fitness for a specific soil to function" will also depend strongly on the climate experienced, how different soils may behave under sequential years of favourable or adverse climate conditions, and considers the quality of the soil's management (Bouma, 2002). The management of the soil will depend on its utilization and historically the intention of good management is that it will maximize what the soil can produce. While agriculture and soil science may have focused on good soil management to maximize production the ecologists and economists working on ecosystems services would argue that good soil management should be to maximize functionality (Robinson et al., 2012). Either way the management of soil over longer periods of time may result in changes to the soil which needs to be accounted for.

Droogers and Bouma (1997) recognized management changes to soil and proposed that soil should be classified according to its genoform and phenoform. The genoform would be a soil in its natural state and recognizes that we know about soil and its genesis. Implicitly they recognized this as a *reference state*. The phenoform would be an account of how a soil has been altered. In particular, the phenoform recognizes the long-term or short-term effects of management changing a soil. Examples include, management resulting in erosion means a soil loss that cannot be returned; or decades of organic farming that increased the organic matter content of soil in the Netherlands (Bouma, 2002).

Usually the genoform would be assumed to be the reference state for a soil but there is a point where soil alteration is so significant and/or permanent (iCannals et al., 2007) that a phenoform may become the reference state. Therefore, the reference state being a soil at a particular categorical level in a soil classification system, under a particular management, could require the recording of both the genoform and phenoform. This recognizes that there exists a soil survey data that defines specific soil types and their position in the landscape and that results for soil quality indicators of different forms of degradation or improvement are characteristically different for different soil types (Bouma et al., 1998).

A reference state is possible if we identify with the logic that makes land evaluation possible (Rossiter, 1996). This acknowledges that land does vary in its physical, social, economic and geographical properties and therefore there are areas more or less suited to it. This variation is systematic and we can map the physical, political, economic and social variation in surveys. This is used to predict how the land will behave with some certainty enabling land suitability to be described and mapped, which then can be used by decision makers to inform their choice of land use (Rossiter, 1996). Semi-quantitative and quantitative approaches have been developed to implement the FAO framework. This has included the LECS system (Elberson and Siderius, 1990), expert systems such as ALES (Rossiter, 1990), and land evaluation by map analysis using geographical information systems (Burrough, 1987). The integration of biophysical and economic disciplines has also been achieved through frameworks such as SOLUS (Bouman et al., 1999) which enables land use to be assessed by quantifying biophysical and economic suitability trade-offs.

From our point of view capability can be measured for a range of soil functions which match the global environmental challenges (CEC, 2006), e.g., *(i) food and other biomass production*; *(ii) storing, filtering and transformation*; *(iii) habitat and gene pool*; *(iv) physical and cultural environment for mankind*; *(v) source of raw materials*; *(vi) acting as carbon pool, and (vii) archive of geological and archaeological heritage*. This requires the establishment of a (local) reference state defined by a genoform at a particular level in a soil classification framework, e.g., family level in Soil Taxonomy, or a specific phenotypical variant of the taxonomically defined genotype due to a particular long-term management. As such capability is largely defined by a set of long(er) time-scale or very slowly varying soil characteristics such as profile form and texture.

3.2. Dimension 2: Condition

The condition of the soil is concerned with the current state of the soil and refers to the shift in capability compared to the reference state. The concept of soil condition strengthened in the 1990s and the current vernacular would refer to soil condition as ‘soil health’ (Karlen et al., 1997). However there is little value in talking about the health of any given soil, unless there is an understanding of how ‘healthy’ it can actually be. Unlike capability, the condition of a soil is contemporary and is measured on a short-term management time scale.

Regulatory bodies and land managers recognize the growing need for information on soil condition so they are informed about (i) the impact of changes in management practices and (ii) justification for investment to maintain or improve the soil resource (Schipper and Sparling, 2000; Wilson et al., 2008). The concepts of soil quality, health, and condition are still being debated in the literature (Wilson et al., 2008) but an example of how regulatory bodies define the soil condition can be taken from the Australian Department of Agriculture, Forestry and Fisheries, thus;

> “Soil condition can be defined as the capacity of a soil to function, within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental health, and promote plant, animal, and human health (Doran and Zeiss, 2000). The condition of a soil can be inferred by measuring specific soil properties (e.g., organic matter content) and by observing soil status (e.g., fertility).”

The United States Department of Agriculture National Resource and Conservation Service (NRCS, USDA) definition using soil quality as an assessment of condition mirrors that above, with a particular noting of the reference condition where *soil is functioning at full capacity under management systems that use Best Management Practices* (NSSH, Part 624.01). We argue that the reference condition should be a combination of soil class (at some taxonomic level) and a management regime.

As with capability, the soil condition will vary in accordance to how it is managed and the nature of the intended use. If the soil is being managed in a way that is consistent with its capability, its condition will be ‘fit for purpose’. For example, in agriculture a soil with high capability can have poor yields resulting from poor management, while a low capability soil through excellent management can produce high yields (Bouma, 2002; Tugel et al., 2005). Similarly, the key to a sustainable use of the soil is to match its intended use with its capability, i.e. soil should not only be viewed through a lens focusing on its ability to produce (Robinson et al., 2012). Therefore, the performance, productivity or functionality of a soil is the sum of its *capability* + *condition*.

$$\textit{performance} = \textit{capability} + \textit{condition}$$

As with soil quality and soil health, the soil condition can be assessed using a set of usually more quickly varying indicators which are commonly grouped as physical, chemical and biological and are linked to a soil function (Doran and Parkin, 1996) and there is a call to adopt standardized methods to evaluate these (Nortcliff, 2002). Minimum data sets of soil physical, chemical and biological properties have been suggested, forming a pre-defined global list of indicators or developed based on site-specific conditions, and there has been an emphasis on measuring the soil chemical and physical properties (Govaerts et al., 2006; Gregorich et al., 1994). Recently, the soil science community's deeper understanding of, and ability to assess, the soil biology has resulted in a suggestion that soil biota in the future may be a significant and broad indicator of the soil's condition (Zak et al., 2003; Barrios, 2007), but this still seems elusive (Pulleman et al., 2012). This is based on the premise that the soil biodiversity reflects the different aspects of soil quality in their composition and function (Valesquez et al., 2007), and a lack or loss of soil biodiversity will compromise the ability for the system to perform certain functions. Alternatively, the central role soil carbon plays in many of the soil functions invites research to see if this is a premium or even a ‘universal’ indicator for soil condition (Stockmann et al., 2013) as there has been research indicating that there are critical limits for soil carbon below which the soil condition is compromised (Loveday and Webb, 2003). If the condition is such that it passes a tipping point or ecological threshold and reaches a state from which it cannot resile then we must recognize a new reference state with a new associated capability (Groffman et al., 2006). Although these are expected there are few examples in the soil literature.

As soil security is a concept of securing soil for the sustainable development of humanity we need to consider more than the biophysical stocks, functioning and ecosystem services, we also need to embrace the economic, social and policy dimensions.

3.3. Dimension 3: Capital

That by placing a capital or monetary value on an asset serves to value or secure that asset seems axiomatic. The concept of capital can be distinguished between five principal forms being, *financial*, *manufactured*, *human*, *social* and *natural* capitals. Of these *natural* capital is the stock of physical and biological resources and is comprised of renewable (e.g. living species), non-renewable (e.g. subsoil assets, such as petroleum and coal), replenishable (e.g. potable water, fertile soils) and cultivated (e.g. crops and forest plantations) natural capitals (Aronson et al., 2007). Since soil provides functions for service delivery placing a value on the soil stocks underpinning these will contribute to an account of its capital (Table 2).

According to Robinson et al. (2009) placing a value on ‘things’ that contribute to human well-being avoids the neglect or omission of a resource or its contribution to the system in any decision-making process. To achieve this there has been a considerable focus on ecosystem services by ecologists (Costanza and Daly, 1992; Daly and Farley, 2003; de Groot et al., 2002; Ekins et al., 2003b; Robinson et al., 2009) with the desire to develop a suitable definition of natural capital, ultimately being ‘*the stock of materials or information contained within an ecosystem*’ (Costanza et al., 1997). Defining natural capital by embracing mass, energy and organization Robinson et al. (2009) found that soil moisture, temperature and structure are valuable stocks, along with inorganic and organic materials (Table 2).

The soil's natural capital is determined by the compositional state of the soil system, *stocks*, which affect the functions provided by the soil for

Table 2
'Natural stocks' of soil refers to the compositional states of the soil that are intrinsic to determine its characteristics (based on Robinson et al., 2009).

Type of service	Indicator	Economic value
Mass		
Solid	*Inorganic material*	
	Mineral stock	Cost of building materials
	Nutrient stock	Replacement costs of fertiliser
	Organic material	
	Carbon stocks	Carbon offsets
	Organisms	Medicines
Liquid	Soil water content	Irrigation & freshwater supplies
Gas	Soil air	?
Energy		
Thermal energy	Soil temperature	?
Biomass energy	Soil Biomass	Relative to carbon with a premium for diversity
Organisation		
Physico-chemical structure	Soil physic-chemical organization, soil structure	Value of increased water holding capacity
Biotic structure	Biological population organization, food webs and biodiversity	Diversity premium – a multiplier for carbon – value of multiplier 2–5
Spatio-temporal structure	Connectivity, patches & gradients	?

the whole ecosystem, the *ecosystem service*. There are also products derived from the ecosystem services produced by the soil which are known as *ecosystem goods*. The stocks as described by Robinson et al. (2009) are outlined in Table 2, and here it can be seen that the economic value of the stock may not always be related to the intrinsic benefit that the stock brings to the soil. For example, a high level or increase in soil organic carbon is crucial for soil function (Stockmann et al., 2013), yet the value of the soil carbon stock is in some cases valued only in its capacity to provide a store of carbon for the purpose of generating an offset through greenhouse gas abatement (McBratney et al., 2012).

As described earlier, ecosystem services fundamentally underpin society and while it is difficult to quantify in economic terms there is a continued effort to refine definitions of their economic value. With the sensible ascription of economic worth that reflects the value of ecosystem services there will be the emergence and further growth in markets that will encourage practices that sustain these public goods. This is challenging, as noted by Brown et al. (2007), who claim that the once held distinction between 'ecosystem services' from 'ecosystem goods' has been obscured by Costanza et al. (1997) who now lump these into a class of 'ecosystem services' after previously noting the distinction between the two. Ecosystem services are derived from ecosystem abiotic and biotic processes and interactions, and while the ecosystem service is derived from its function an ecosystem good is concerned with its concrete nature, e.g. rocks, plants, soil, water, and recreation. Therefore directly attributing ecosystem goods in an account of natural capital and to soil alone remains difficult (McBratney et al., 2012).

Economic value of minerals and energy sources below soil are well established, but because the intrinsic value of the soil itself is not known, or its potential productivity, the case for securing soil in a multi-land use context is difficult to make. There is the need for placing an economic value on the soil asset, which refers to the value of the soil itself, as well as, the value of its potential performance given its capability. Placing a value on the soil itself, as with ecosystem services (Boyd and Banzhaf, 2007), would mean isolating its value from non-soil contributions, such as labour or financial and manufactured capital. Dominati et al. (2010) propose a framework for quantifying the natural capital of soil and note that care needs to be taken when defining what the soil stocks are as opposed to the flows, or services. In particular the framework intends to incorporate the scientific contemporary understanding of soil processes and taxonomy, linking these with each ecosystem service that needs to be paired with economic valuation.

There is also a component of *cultivated* natural capital arising from the soil: the commodities that underpin agriculture and forestry as enterprises (Aronson et al., 2007). We are most familiar with this kind of capital, however we still need to evaluate the component of that capital that can be attributed to soil. The kind of simulation models that can be used to evaluate the effects of soil capability and condition, e.g., for crop production, can also be used to evaluate this component of capital for soil at a reference state or any other condition.

3.4. Dimension 4: Connectivity

Connectivity brings in a social dimension around soil. In part it is concerned with whether the person who is responsible for the soil in any given piece of land has the right knowledge and resources to manage the soil according to its capability. It also acknowledges that the effect of this '*stewardship*' of this soil is long term and therefore consideration needs to be given to intergenerational equity. This may involve the adoption of a precautionary principle acknowledging soil as a non-renewable resource and recognizing that there is still more to know about the soil and its role in managed and non-managed ecosystems. It also raises the question regarding the need for a soil ethic and in doing so whether soil should only be valued for the well-being of humans (Thompson, 2011). This is all informed by the knowledge of those who use and research soil, which needs to be supported by appropriate education strategies and suitable communication.

It could be argued that if there is no connection to the soil then the soil itself may not be valued and is prone to not being managed to its best condition. On obvious illustration of this is the claim that the lack of '*land tenure*' or other cognate forms of ownership, e.g. social capital, more often than not will result in the soil use being less than optimal (Katz, 2000). The connection that land tenure provides is assumed to promote better land management (Fraser, 2004) and the lack of satisfactory land-tenure policies, or long-term leasing, has been blamed for the poor performance in the agricultural sector and environmental protection (Burgi, 2008). Incomplete policies or instruments of land tenure may also affect how land is allowed to be used, and the loss of land as a public good to less than optimal private land use activities has led to soil degradation and loss of ecosystem services (Fitzherbert et al., 2008). The contribution of land tenure to soil security needs to be integrated with knowledge of the soil's capability, current condition and its natural capital. This will depend on the land use manager knowing how to optimise the use of the soil system within the economic, environmental and social constraints and having access to others with good soil science knowledge who can advise on needed management change.

Transfer of soil science knowledge and skills has to do more than just provide acceptable solutions to complex problems; those with soil science knowledge also have to be able to identify what the needs are and follow this with effective communication of the solutions. Historically, knowledge extension relied primarily on technology transfer and formal training (NAFES, 2005; Knickel et al., 2008; Lacy, 2011). Ridley (2007) reports that Coutts et al. (2004) developed five types of extension being: 1) group empowerment facilitation, 2) technology transfer, 3) programmed learning, 4) information access, and 5) personalized consultation. The shift from the primary reliance on technology transfer (e.g. type 2) to more participatory and facilitatory approaches (e.g. type 1) is driven by the realization that soil cannot be viewed merely from a production point of view and must be valued as stock that provides for other services; *see previous sections defining capability and capital.*

Those connected with the soil are also deriving their information from multiple sources, including: researching information sources, talking with extension providers, undertaking formal education, and consulting other support services (Rivera et al., 2005). This has occurred in an environment with an increasing number of non-government supported providers (Knickel et al., 2008). The complexity ensuing from competition between providers and use of multiple sources and their sophisticated interactions mean that knowledge transfer can't be viewed any longer as a linear process and now requires more systemic approaches (e.g. types 1, 4 & 5). Irrespectively, this reliance on sharing of knowledge between these sources (Lawrence et al., 2007) could be addressed by a new approach identified as *Extension-2.0* which involves *Knowledge Brokers* who in this case are those with 'hard knowledge and social intelligence' who can provide relevant soil science advice (Bouma et al., 2011). The continued engagement of these knowledge brokers would facilitate collaboration between research and education communities and those who require this knowledge so that change can be collaboratively addressed (Stockmann et al., 2013).

Soil science is integral to many of the challenges faced by managed and non-managed systems and the society that depends on these (Bouma, 2001; Hartemink and McBratney, 2008). The demand for those with good soil knowledge is high (Havlin et al., 2010), and the teaching of the discipline is mainly housed in geology, geography, environmental science and agriculture programmes (Brevik, 2009) contributing successfully to these areas (Hopmans, 2007). Smiles et al. (2000) noted that the future challenge for soil science education is to stimulate curiosity and innovation as well as a good grounding in existing knowledge (Field et al., 2010). Because soil science has a broad holistic role in society and has to be involved with scientists from other disciplines, policy experts and users of the soil itself (Field et al., 2011), the context of the education must be broad.

There is an expectation that work-ready soil science graduates will have knowledge in the physical, chemical and biological processes of the soil, can advise on management of soils in ecosystems, understand water movement in soils and its impact on water quality, as well as, problem solve with scientific reasoning, with reliable data collecting and analysis skills, and be able to communicate these sufficiently to the broader community (Jarvis et al., 2012). Smiles et al. (2000) identify the need for soil science education as problem solving, being able to interact with political influence and policy settings, while maintaining its discipline development and innovation. A set of teaching principles have now been developed in response to this educational need (Field et al., 2011) and Bouma and McBratney (2013) state that the implementation of this approach to soil science education is a move towards producing graduates with the knowledge and skills being asked of by society.

The second, and some might argue even more important, aspect of connectivity is 'How does or can society connect to the soil?' How do individuals in society who are not managing or directly dependent on the soil have or develop a relationship with the soil? How does soil project itself into society? Underlying this is the notion that those who know care, and those who care lobby. It can be said that how soil is enmeshed in the past and the future of our society is not known by those outside the discipline (Janzen et al., 2011). How will soil data applications developed for mobile technologies, such as Soil-Web (Beaudette and O'Geen, 2009) and those that rely on crowd sourced soil data (Shelley et al., 2013) contribute to this? This aspect of connectivity for soil security is perhaps the least developed of all the concepts we synthesise in this paper and therefore there are few references in the literature. An example may help. Take an area of soil and identify all those who consume the product of that soil. The map of all those individuals is the societal footprint for that soil. This connection can be achieved by the concepts of traceability in supply chains. To make soil more secure we need to have a mechanism for the users of this soil product to know and understand the soil aspect of the soil product and feedback. Through new social media, and crowd-sourcing, these people will talk to each other, back to the producers and to the regulators. The older concept of *terroir* in viticulture explains the potential link between society and particular areas of soil through a highly valued product wine — the security of soil linked to particular *terroir* is societally stronger.

3.5. Dimension 5: Codification

No matter how secure soil may be through proper management of condition, valuing the capital and connectivity to society there still remains the need for public policy and regulation, at least as a safety net, and at best to synergise and positively feed back into the other aspects of soil security (dimensions). An example here is policies around recognition and payment for public goods such as ecosystem services provided by soil to landholders by governments on behalf of society. The potential synergies include improved management, increase in natural capital, improved education and societal connectivity. Carrots are to be preferred to sticks.[1]

The ever-changing environment of soil, its uses and technological advances result in very complex and difficult challenges, so good policy and policy decisions are dependent on including the appropriate stakeholders who will be able to articulate these challenges, and which are framed so that they can translate the *codified k*nowledge, in this case, soil science knowledge into improved and more effective ways to provide practical solutions (Grímsson, 2007). This relies on the willingness for the community of scientists to collaborate with government authorities and the private sector. The challenge for those with soil science knowledge is to recognize that this engagement is not necessarily about what is 'right' or 'wrong' but being willing to also accept that good policy may be made on decisions of what is 'better' or 'worse' (Bouma et al., 2011) and as identified earlier this can be facilitated by the knowledge brokers.

For codification to be implemented it is important to be aware of the policy cycle which can be summarized as a series of functions, identified as: *signalling*, *design*, *decision*, *implementation* and *evaluation* (Bouma and Droogers, 2007). When engaging with the policy space it is clear that the signals that are used to identify problems come from a wide range of sources and stakeholders. The design phase is where the call for good soil science knowledge and input from those with this knowledge is required, and this knowledge should be based on the dimensions of capability, condition, capital and connectivity. The use of scientific principles and standards framing policies and laws that can be implemented has resulted from good cooperation between soil scientists and environmental lawyers (Hannam, 2007).

There have been a number of initiatives to give soil a stronger policy focus. The World Soils Policy leading to the World Soil Charter was developed in the early 1980s focusing on a set of principles on management of the land resource to improve their productivity and conservation for future generations (FAO, 1982). This resulted in United Nation's Environmental Programme (UNEP) assessing global and regional soil degradation which was published as the World Atlas of Desertification (UNEP, 1997). Doran and Jones (1996) noted that protecting soil quality should be as fundamental a goal as protecting air and water quality. The International Union of Soil Sciences developed the World Soils Agenda focusing on three tasks, being: science, policy and implementation. The science was focused on monitoring degradation, developing appropriate indicators and proposing technologies and approaches to enable frameworks for sustainable land management. The policy task produced an agenda of identifying an international multi-disciplinary network, along with an inter-government panel on soils, and to provide advice, develop and implement national soil policies (Hurni and Meyer, 2002). The Millennium Ecosystem Assessment (2005) noted that extrinsic policies related to global trade regimes and food production had a direct and indirect effect on soil degradation.

The mixed success of early soil conservation work has been influenced by too much emphasis on a top-down approach, exacerbated by a lack of local involvement and the curing of symptoms rather than causes (Arnalds and Runólfsson, 2007). Hannam (2007) has also noted that these efforts to develop policies that could be used as

---

[1] Amusingly, even this metaphor recognizes soil products.

instruments in legal and policy frameworks to protect the soil may still be deficient. Irrespectively, Hannam (2007) did identify that there have been considerable efforts at the national level that could be used as exemplars and an ever-increasing use of key multilateral and regional agreements for soil management.

It can be seen from the history described above that policies for soil conservation and protection have focused primarily on soil erosion and secondly soil fertility. More recently, in 2011, the FAO launched that Global Soil Partnership (GSP) in conjunction with the European Commission with a focus on sustainable management of soil resources for two of the six global environmental challenges, namely, food security and climate-change abatement (Global Soil Partnership, 2012; Koch et al., in press). This broadening of engagement in policy and legislative development is welcomed and is crucial to inform the future development of codification to secure the soil.

4. Discussion

Building a framework using these dimensions will enable us to determine if the soil is working to its capacity and is in a good condition. Securing the soil will require us to value it and the potential goods and services it can produce. This will require people who are benefiting from the soil to be aware of their connection to it, and when necessary, the soil to be supported by good policy and regulation.

As noted earlier there are existing concepts which have been proposed that are similar to soil security, namely: *Soil Quality*, *Soil Health* and *Soil Protection*.

For the past fifteen years, the soil science community has discussed the notion of 'soil quality' — defined in terms of the chemical, physical and biological aspects of soil (Karlen et al., 2001) and a comprehensive set of indicators has been identified to assess the physical, chemical and biological properties that affect soil quality (Andrews et al., 2002). A framework has been proposed to select these indicators that are to be used to measure soil quality and the choice from this universal set of indicators is contextual (Karlen et al., 2003). This is demonstrated by the development of Soil Management Assessment Framework (SMAF), soil quality score cards or soil quality kits for farmers and education (Andrews et al., 2004). For the past five years, the discussion has centred on the idea of '*Soil Health*', defined largely in biological terms (Doran and Safley, 1997). It has come to reflect a set of biological indicators (Doran and Ziess, 2000). This is reflected in the preponderance of effort on measures of the soil biological diversity which more than likely coincides with the rise in new gene-sequencing techniques. The scientific evidence for directly linking soil microbial biodiversity and soil functions is still growing, except for the concept that diverse soil may have a tendency for higher disease suppression (van Bruggen and Semenov, 2000). Both concepts of quality and health are focused on assessing the soil condition, but there is no explicit statement of a reference state or the incorporation of this into a soil quality or soil health framework. This was the implied objection of Sojka et al. (2003).

The European Union Soil Protection Strategy is based on soil function and the threats to soil. As described earlier (Bouma and Droogers, 2007), there are seven functions defined. If we consider soil security, the function of the soil to (i) produce food and other biomass would be related to soil capability and soil condition, while soil capital would relate to (ii) storing, filtering and transformation and (iii) the provision for a habitat and gene pool. The cultural environment for mankind (iv) is related to soil connectivity and valued through the soil capital, where (vi) acting as a carbon pool is related to soil condition and capital, and being an archive for archeological heritage (vii) is covered by soil condition and its connectivity. Although described as a function we would consider (v) source for raw materials, as a threat. The European Commission has identified five threats classified as erosion, compaction, contamination, organic matter decline, salinization, landslides, and surface sealing. Many of these would relate largely to soil condition, capability and capital. A non-exhaustive wider list of threats to soil security is given in Table 3 and clearly, in any given situation, an evaluation of the likelihood or intensity of these threats needs to be made.

Table 3
A list of threats to soil security.

Dimension	Threats to soil security
Capability	Erosion, landslides, sealing by infrastructure, source of raw materials
Condition	Contamination, loss of organic matter, compaction and other physical soil degradation, salinization, floods
Capital	Inadequate assessment of the value of the soil asset, *soil stock*, and the processes that: *support* (e.g. nutrient & water cycling, biological activity), *degrade* (e.g. acidification, salinization, loss of organic matter, compaction), and *regulate* (flood mitigation, erosion, control soil pests and disease, & greenhouse gas abatement)
	Indiscriminate treatment of soil as a renewable resource
Connectivity	Inadequate soil knowledge of land managers,
	lack of recognition of soil services and soil goods by society
Codification	Incomplete policy framework
	Inadequate or poorly designed legislation

It is clear that the concepts of soil quality, health and protection are directly and implicitly related to the concept of soil security and its dimensions, but we would suggest that the soil security concept is wider with clear dimensions to frame the value of soil and how people interact with it. Most importantly the soil security concept is strengthened by the proposal of the soil capability, capital, connectivity and codification dimensions, which are not explicitly identified in the other concepts being compared.

5. Conclusions & future work

1. Soil has an integral part to play in the global environmental sustainability challenges of food security, water security, energy security, climate stability, biodiversity, and ecosystem services. Indeed, soil has the same existential status as these issues and should be highlighted and treated similarly.
2. There is an imperative for a concept of soil that is similar to food, water and energy security. We have proffered the term *soil security*.
3. The concept of soil security is multi-dimensional. It recognizes capability, condition, capital, connectivity and codification of soil entities and encompasses the social, economic and biophysical sciences.
4. Soil security is a wider, more integrative, concept than 'soil quality', 'soil health' or 'soil protection'.
5. There is a persuasive need for developing a thorough risk-based framework for assessing soil security locally, regionally, nationally and globally using the dimensions of capability, condition, capital, connectivity and codification.

There is a lot of work needed to develop this concept into a fully developed risk-based soil security assessment and policy framework. For each one of those dimensions there are some burning questions. For example, *Capability & condition*, how can we arrive at an agreed methodology for defining the reference state? *Capital*, can we realise a production and natural capital view of the soil asset? *Connectivity*, which new soil education approaches could be devised to connect land managers and the public appropriately to soil? And *Codification*, to what degree is formal regulation necessary to achieve sustainable use of soil in which other policies could be utilized?

As a final observation, an assessment framework for soil security should be risk based in the sense that it should recognize and utilize the uncertainties in the assessment of each of the dimensions and their combination.

Acknowledgements

The authors wish to acknowledge input from the Soil Carbon Initiative at the United States Study Centre and the encouragement of Professor Robert Hill, and support provided by the Australian Research

Council Discovery project 'Global Space–Time Soil Carbon Assessment'. We also wish to acknowledge the invaluable feedback provided by the reviewers.

References

Alrøe, H.F., Kristensen, E.S., 2002. Towards a systemic research methodology in agriculture: rethinking the role of values in science. Agric. Hum. Values 19, 3–23.

Andrews, S.S., Karlen, D.L., Mitchel, J.P., 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California Agriculture. Ecosyst. Environ. 90, 25–45.

Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework. Soil Sci. Soc. Am. J. 68, 1945–1962.

Anonymous, 2008. A fresh approach to water. Nature 452, 253.

Arnalds, A., Runólfsson, S., 2007. Iceland's century of conservation and restoration of soils and vegetation. Proceedings of the International Forum Celebrating the Centenary of Conservation and Restoration of Soil and Vegetation in Iceland, Selfoss, Iceland. Soils, Society & Global Change, pp. 70–74.

Aronson, J., Milton, S.J., Blignaut, J.N., 2007. Restoring natural capital: definition and rationale. In: Aronson, J., Milton, S.J., Blignaut, J.N. (Eds.), Restoring Natural Capital: Science, Business and Practice. Island Press, Washington, DC, USA.

Balmford, A., Bennun, L., ten Brink, B., Cooper, D., Côte, I.M., Crane, P., Dodson, A., Dudley, N., Dutton, I., Green, R.E., Gregory, R.D., Harrison, J., Kennedy, E.T., Kremen, C., Leader-Williams, N., Lovejoy, T.E., Mace, G., May, R., Mayaux, P., Morling, P., Phillips, J., Redford, K., Ricketts, T.H., Rodriguez, J.P., Sanjayan, M., Schei, P.J., van Jaarsveld, A.S., Walther, B.A., 2005. The convention on biological diversity's 2010 target. Himal. J. Sci. 9, 43–45.

Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecol. Econ. 64, 269–285.

Beaudette, D.E., O'Geen, A.T., 2009. Soil-Web. An online soil survey for California, Arizona and Nevada. Comput. Geosci. 35, 2119–2128.

Bouma, J., 1989. Using soil survey data for quantitative land evaluation. Adv. Soil Sci. 9, 177-123.

Bouma, J., 2001. The new role of soil science in a network society. Soil Sci. 166, 874–879.

Bouma, J., 2002. Land quality indicators of sustainable land management across scales. Agric. Ecosyst. Environ. 88, 129–136.

Bouma, J., Droogers, p., 2007. Translating soil science into environmental policy: a case study on implementing the EU soil protection strategy in the Netherlands. Environ. Sci. Pol. 10, 454–463.

Bouma, J., McBratney, A.B., 2013. Framing soils as an actor when dealing with wicked environmental problems. Geoderma 200–201, 130–139.

Bouma, J., Batjes, N.H., Groot, J.J.R., 1998. Exploring land quality effects on world food supply. Geoderma 86, 43–59.

Bouma, J., van Altvorst, A.C., Eweg, R., Smeets, P.J.A.M., van Latesteijn, H.C., 2011. The role of knowledge when studying innovation and the associated wicked sustainability problems in agriculture. Adv. Agron. 113, 293–323.

Bouma, J., Stoorvogel, J.J., Sonneveld, W.M.P., 2012. Land evaluation for landscape units. In: Huang, P.M., Li, Y., Summer, M. (Eds.), Handbook of Soil Science. CRC Press, Boca Raton London, New York, pp. 34-1–34-22.

Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Nieuwenhuyse, A., Hengsdijk, H., Bouma, J., 1999. A framework for integrating biophysical and economic land use analysis at different scales. Agric. Ecosyst. Environ. 75, 55–73.

Boyd, J., Banzhaf, S., 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecol. Econ. 63, 616–626.

Brevik, E.C., 2009. The teaching of soil science in geology, geography, environmental science, and agricultural programs. Soil Surv. Horiz. 50, 120–123.

Brown, T.C., Bergstrom, J.C., Loomis, J.B., 2007. Defining, valuing, and providing ecosystem goods and services. Nat. Resour. J. 47, 329–376.

Brussaard, L., de Ruiter, P.C., Brown, G.G., 2007. Soil biodiversity for agricultural sustainability. Agric. Ecosyst. Environ. 121, 233–244.

Burgi, J.T., 2008. The dynamics of tenure security, agricultural production and environmental degradation in Africa: evidence from stakeholders in north-east Ghana. Land Use Policy 25, 271–285.

Burrough, P.A., 1987. Mapping and map analysis: new tools for land evaluation. Soil Use Manag. 3, 20–25.

Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc. Natl. Acad. Sci. 104, 18866–18870.

Carter, M.R., Gregorich, E.G., Anderson, D.W., Doran, J.W., Janzen, H.H., Pierce, F.J., 1997. Concepts of soil quality and their significance. In: Gregorich, E.G., Carter, M.R. (Eds.), Soil Quality for Crop Production and Ecosystem Health. Developments in Soil Science 25. Elsevier, Amsterdam, pp. 1–19.

Chen, J., 2007. Rapid urbanization in China: a real challenge to soil protection and food security. Catena 69, 1–15.

Commission of the European Communities (CEC), 2006. Proposal for a Directive of the European Parliament and of the Council, establishing a framework for the protection of soil and amending Directive 2004/35/EC. Com 231 final, Brussels.

Convention on biological diversity, 1992. Earth Summit 30619. United Nations, Rio De Janeiro.

Cordell, D., Drangert, J., White, S., 2009. The story of phosphorus: global food security and food for thought. Glob. Environ. Chang. 19, 292–305.

Costanza, R., Daly, H.E., 1992. Natural capital and sustainable development. Conserv. Biol. 6, 37–46.

Costanza, R., dArge, R., de Groot, R., Farber, S., Grasson, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Coutts, J., Roberts, K., Frost, F., Coutts, A., 2004. Extension for capacity building. A review of extension in Australia and its implications for developing capacity into the future. Final Report for Cooperative Venture for Capacity Building.

Daily, G.C., 1999. Developing a scientific basis for managing Earth's life support systems. Conserv. Ecol. 3, 14.

Daly, H.E., 1979. On thinking about the future energy requirements. In: Unseld, C.T. (Ed.), Sociopolitical Effects of Energy Use and Policy. National Academy of Science, Washington, DC, pp. 232–240.

Daly, H.E., Farley, J., 2003. Ecological Economics: Principles and Applications. Island Press, Washington, DC, USA.

Davidson, E., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 404, 165–173.

De Groot, R., 1992. Functions of Nature: Evaluation of Nature in Environmental Planning Management and Decision Making. Wolters-Noordhoff, Groningen.

De Groot, R., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41, 393–408.

Dominati, E., Patterson, M., MacKay, A., 2010. A framework for classifying and qualifying the natural capital and ecosystem services of soils. Ecol. Econ. 69, 1858–1868.

Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agric. Ecosyst. Environ. 88, 119–127.

Doran, J.W., Jones, A.J., 1996. Preface. Methods for Assessing Soil Quality.Soil Science Society of America Special Publication, Madison, Wisconsin, USA xi–xiii.

Doran, J.W., Parkin, T.B., 1996. Quantitative indicators of soil quality: a minimum data set. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality, 49. Soil Science Society of America Sp. Publ, pp. 25–37.

Doran, J.W., Safley, M., 1997. Defining and assessing soil health and sustainable productivity. In: Pankhurst, C., Doube, B.M., Gupta, V.V.S.R. (Eds.), Biological Indicators of Soil Health. CSIRO Publishing, pp. 1–28.

Doran, J.W., Ziess, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil Ecol. 15, 3–11.

Droogers, P., Bouma, J., 1997. Soil survey input in exploratory modelling of sustainable soil management practices. Soil Sci. Soc. Am. J. 61, 1704–1710.

Ekins, P., Simon, S., Deustsch, L., Folke, C., de Groot, R., 2003a. A framework for the practical application of the concpets of critical natural capital and strong sustainability. Ecol. Econ. 44, 165–185.

Ekins, P., Folke, C., de Groot, R., 2003b. Identifying critical natural capital. Ecol. Econ. 44, 159–163.

Ekschmitt, K., Griffiths, B.S., 1998. Soil biodiversity and its implications for ecosystem functioning in a heterogeneous and variable environment. Appl. Soil Ecol. 10, 201–215.

Ekschmitt, K., Stierhof, T., Dauber, J., Kreimes, K., Wolters, V., 2003. On the quality of soil biodiversity indicators: abiotic and biotic parameters as predictors of soil faunal richness at different spatial scales. Agric. Ecosyst. Environ. 98, 273–283.

Elberson, G.W.W., Siderius, W., 1990. Experiences with FAO's land evaluation computer system (LECS) in different environments. Transactions 14th International Congress of Soil Science, Kyoto, Japan, vol. VII, pp. 290–295.

Falkenmark, M., 2001. The greatest water problem: the inability to link environmental security, water security and food security. Water Resour. Dev. 17, 539–554.

Falkenmark, M., Rockström, J., 2006. The new blue and green water paradigm: breaking new ground for water resources planning and management. J. Water Resour. Plan. Manag. 132, 129–132.

FAO, 1976. A framework for land evaluation. Soils Bulletin, 32. FAO, Rome.

FAO, 1982. World Soil Charter. FAO, United Nations Publication.

FAO, 1983. Guidelines: land evaluation for rainfed agriculture. Soils Bulletin, 52. FAO, Rome.

FAO, 1984. Land evaluation for forestry. Paper 48.FAO, Rome.

FAO, 1985. Guidelines: land evaluation for irrigated agriculture. Soils Bulletin, 55. FAO, Rome.

FAO, 1991. Guidelines: land evaluation for extensive grazing. Soils Bulletin, 58. FAO, Rome.

Fedoroff, N.V., Battisti, D.S., Beachy, R.N., Cooper, P.J.M., Fischhoff, D.A., Hodges, C.N., Knauf, V.C., Lobell, D., Mazur, B.J., Molden, D., Reynolds, M.P., Ronald, P.C., Rosegrant, M.W., Sanchez, P.A., Vonshak, A., Zhu, J.K., 2010. Radically rethinking agriculture for the 21st century. Science 327, 833–834.

Field, D.J., Koppi, T., McBratney, A.B., 2010. Producing the thinking soil scientist. Proceedings 19th World Congress of Soil Science, August, Brisbane, Australia.

Field, D.J., Koppi, A.J., Jarrett, L.E., Abbott, L.K., Cattle, S.R., Grant, C.D., McBratney, A.B., Menzies, N.W., Weatherly, A.J., 2011. Soil science teaching principles. Geoderma 167–168, 9–14.

Filip, Z., 2002. International approach to assessing soil quality by ecologically-related biological parameters. Agric. Ecosyst. Environ. 88, 169–174.

Fitzherbert, E.B., Struebig, M.J., Morel, A., Danielsen, F., Brühl, C.A., DonaldP, F., Phalan, B., 2008. How will oil palm expansion affect biodiversity? Trends Ecol. Evol. 23, 538–545.

Fraser, E.D.G., 2004. Land tenure and agricultural management: soil conservation on rented and owned fields in southwest British Columbia. Agric. Hum. Value 21, 73–79.

Gallagher, K.S., Grübler, A., Kuhl, L., Nemet, G., Wilson, C., 2012. The energy technology innovation system. Annu. Rev. Environ. Resour. 35, 77–108.

Global Soil Partnership, 2012. Towards a global soil partnership for food security and climate change mitigation and adaptation. Background Paper. (http://www.fao.org/nr/water/down/GSP_Background_Paper.pdf).

Godfray, H.C.J, Breddington, J.R., Crute, I.R., Haddad, L., Lawerence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, A.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.

Govaerts, B., Sayre, K.D., Deckers, J., 2006. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil Tillage Res. 87, 163–174.

Gregorich, E.G., Carter, M.R., Doran, J.W., Pankhurst, C.E., Dwyer, L.M., 1994. Towards a minimum data set to assess soil organic carbon in agricultural soils. Can. J. Soil Sci. 74, 367–386.

Grímsson, Ò.R., 2007. Sharing knowledge and experience. Proceedings of the International Forum Celebrating the Centenary of Conservation and Restoration of Soil and Vegetation in Iceland, Selfoss, Iceland. Soils, Society & Global Change, pp. 9–12.

Groffman, P., Baron, J., Blett, T., Gold, A., Goodman, I., Gunderson, L., Levinson, B., Palmer, M., Paerl, H., Peterson, G., LeRoy Poff, N., Rejeski, D., Reynolds, J., Turner, M., Weathers, K., Wiens, J., 2006. Ecological thresholds: the key to successful environmental management or an important concept with no practical application? Ecosystems 9 (1), 1–13.

Hannam, I., 2007. Capacity building for developing legal and policy frameworks for soil conservation and protection. Proceedings of the International Forum Celebrating the Centenary of Conservation and Restoration of Soil and Vegetation in Iceland, Selfoss. Soils, Society & Global Change, pp. 93–98.

Hartemink, A.E., McBratney, A.B., 2008. A soil science renaissance. Geoderma 148, 123–129.

Hatfield, J.L., Sauer, T.J., Prueger, J.H., 2001. Managing soils to achieve greater water use efficiency: a review. Journal of Agronomy 93, 271–280.

Havlin, J., Balster, N., Chapman, S., Ferris, D., Thompson, T., Smith, T., 2010. Trends in soil science education and employment. Soil Sci. Soc. Am. J. 74, 1429–1432.

Herrick, J.E., 2000. Soil quality: an indicator of sustainable land management? Appl. Soil Ecol. 15, 75–83.

Hopmans, J.W., 2007. A plea to reform soil science education. Soil Sci. Soc. Am. J. 71, 639–640.

Hurni, H., Meyer, K. (Eds.), 2002. A World Soils Agenda, Discussing International Actions for the Sustainable Use of Soils, IASUS Working Group of the International Union of Soil Sciences (IUSS). Centre for Development and Environment, Berne.

iCannals, L.M., Bauer, C., Depestele, J., Dubreuil, A., Knuckel, R.F., Gaillard, G., Michlesen, O., Müller-Wenk, R., Rydgren, B., 2007. Key elements in a framework for land use impact assessment with LCA. Int. J. LCA 12, 5–15.

Janzen, H.H., Fixen, P.E., Franzluebbers, A.J., Hattey, J., Izaurralde, E.C., Ketterings, Q.M., Lobb, D.A., Schlesinger, W.H., 2011. Global prospects rooted in soil science. Soil Sci. Soc. Am. J. 75, 1–8.

Jarvis, H.D., Collett, R., Wingenbach, G., Heilman, J.L., Fowler, D., 2012. Developing a foundation for constructing new curricula in soil, crop, and turfgrass sciences. J. Nat. Res. Life Sci. Educ. 41, 7–14.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Sci. Soc. Am. J. 61, 4–10.

Karlen, D.L., Andrews, S.S., Doran, J.W., 2001. Soil quality: current concepts and applications. Adv. Agron. 74, 1–39.

Karlen, D.L., Ditzer, G.A., Andrews, S.S., 2003. Soil quality: why and how? Geoderma 114, 145–156.

Katz, E.G., 2000. Social capital and natural capital: a comparative analysis of land tenure and natural resource management in Guatemala. Land Econ. 76, 114–132.

Knickel, K., Brunori, G., Rand, S., Proost, J., 2008. Towards a better conceptual framework for innovation processes in agriculture and rural development: from linear models to systemic approaches. WS 6: Change in Knowledge Systems and Extension Services: Role of New Actors. 8th European IFSA Symposium, Clermont-Ferrand, France.

Koch, A., McBratney, A.B., Adams, M., Field, D.J., Hill, R., Lal, R., Abbott, L., Angers, D., Baldock, J., Barbier, E., Bird, M., Bouma, J., Chenu, C., Crawford, J., Flora, C.B., Goulding, K., Grunwald, S., Jastrow, J., Lehmann, J., Lorenz, K., Minansy, B., Morgan, C., O'Donnell, A., Parton, W., Rice, C.W., Wall, D.H., Whitehead, D., Young, I., Zimmermann, M., 2013. Soil security: solving the global soil crisis. Glob. Policy J. (in press).

Lacy, J., 2011. Cropcheck: farmer benchmarking participatory model to improve productivity. Agric. Syst. 104, 562–571.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1–22.

Lal, R., 2010a. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience 60, 708–712.

Lal, R., 2010b. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. Food Secur. 2, 169–177.

Lavelle, P., Decaëns, T., Auberts, M., Barot, S., Blouin, M., Bureau, F., Margerie, P., Mora, P., Rossi, J.P., 2006. Soil invertebrates and ecosystem services. Eur. J. Soil Biol. 42, S3–S15.

Lawrence, D., Christodoulou, N., Whish, J., 2007. Designing better on-farm research in Australia using a participatory workshop process. Field Crop Res. 104, 157–164.

Legros, G., Havet, I., Bruce, N., Bonjour, S., 2009. The Energy Access Situation in Developing Countries: A Review Focusing on the Least Developed Countries and Sub-Saharan Africa. Health Organisation, UN Development Program, New York.

Loveday, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil Tillage Res. 70, 1–18.

Luck, G.W., Daily, G.C., Ehrlich, P.R., 2003. Population diversity and ecosystem services. Trends Ecol. Evol. 18, 331–336.

McBratney, A.B., Minasny, B., Wheeler, I., Malone, B.P., 2012. Frameworks for digital soil assessment. In: Minasny, B., Malone, B.P., McBratney, A.B. (Eds.), Digital Soil Assessment and Beyond. Taylor & Francis Group, London, pp. 9–14.

Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and Human Well-being: Desertification Synthesis. World Resources Institute, Washington, D.C.

Mooney, H.A., Ehrilch, P.R., 1997. Ecosystem services: a fragmentary history. In: Daily, G.C. (Ed.), Natures Services: Societal Dependence on Natural Ecosystems. Island Press, Washington DC, USA, pp. 11–19.

Morison, J.I.L., Baker, N.R., Mullineaux, P.M., Davies, W.J., 2008. Improving water use in crop production. Philos. Trans. R. Soc. Biol. Sci. 363, 639–658.

Mulder, C., 2006. Driving forces from soil invertebrates to ecosystem functions: the allometric perspective. Naturwissenschaften 93, 467–479.

NAFES, 2005. Consolidating Extension in the Lao PDR. National Agricultural and Forestry Extension Service, Vientiane, Laos.

Noël, J.F., O'Connor, M., 1998. Strong sustainability: towards indicators for sustainability of critical natural capital. In: Faucheux, S., O'Connor, M. (Eds.), Valuation for Sustainable Development: Methods and Policy Indicators. Edward Elgar, Cheltenham, pp. 75–97.

Nortcliff, S., 2002. Standardisation of soil quality attributes. Agric. Ecosyst. Environ. 88, 161–168.

NSSH, Soil Quality Concepts (624.01) (In) Soil Quality, Part 624. http://soils.usda.gov/technical/handbook/contents/part624.html

Palm, C., Sanchez, P., Ahamed, S., Awiti, A., 2007. Soils: a contemporary perspective. Annu. Rev. Environ. Resour. 32, 99–129.

Patzel, N., Sticher, H., Karlen, D.L., 2000. Soil fertility — phenomenon and concept. J. Plant Nutr. Soil Sci. 163, 129–142.

Pinstrup-Anderson, P., 2009. Food security: definition and measurement. Food Secur. 1, 5–7.

Pretty, J., Toulmin, C., Williams, S., 2011. Sustainable intensification in African agriculture. Int. J. Agric. Sustain. 9, 5–24.

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., Rutgers, M., 2012. Soil biodiversity, biological indicators and soil ecosystem services — an overview of European approaches. Curr. Opin. Environ. Sustain. 4, 529–538.

Ridley, A.M., 2007. Preparing Australian broadacre agriculture for environmental scrutiny using Environmental Management Systems: implications for extension services. Aust. J. Exp. Agric. 47, 367–377.

Rivera, W.M., Qamar, M.K., Mwandemere, H.K., 2005. Enhancing Coordination among AKIS/RD Actors: An Analytical and Comparative Review of Country Studies on Agricultural Knowledge and Information Systems for Rural Development. FAO, Rome.

Robinson, D.A., Lebron, I., Vereecken, H., 2009. On the definition of the natural capital of soils: a framework for description, evaluation and monitoring. Soil Sci. Soc. Am. J. 73, 1904–1911.

Robinson, D.A., Hackley, N., Dominati, E.J., Lebron, I., Scow, K.M., Reynolds, B., Emmett, B.A., Keith, A.M., de Jonge, L.W., Schjonning, P., Moldrup, P., Jones, S.B., Tuller, M., 2012. Natural capital, ecosystem services, and soil change: why soil science must embrace an ecosystems approach. Vadose Zone J. 11, 5–10.

Rockström, J., Falkenmark, L., Hoff, H., Rost, S., Gerten, D., 2009. The future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resource Research 45 (W00A12), 1–16.

Rossiter, D.G., 1990. *ALES*: a framework for land evaluation using a microcomputer. Soil Use Manag. 6, 7–20.

Rossiter, D.G., 1996. A theoretical framework for land evaluation. Geoderma 72, 165–190.

Scherr, S., 1999. Soil degradation: a threat to developing countries food security by 2020. Food, Agriculture, Environment Discussion Paper 27.International Food Policy Research Institute, Washington DC, U.S.A.

Schipper, L.A., Sparling, G.P., 2000. Performance of soil condition indicators across taxonomic groups and land uses. Soil Sci. Soc. Am. J. 64, 300–311.

Schjønning, P., Elmholt, S., Christensen, B.T., 2004. Soil quality management — concepts and terms. In: Schjønning, P., Elmholt, S., Christensen, B.T. (Eds.), Managing Soil Quality: Challenges in Modern Agriculture. CABI Publishing, UK, pp. 1–17.

Shelley, W., Lawlay, R., Robinson, D.A., 2013. Technology: crowd-sourced soil data for Europe. Nature 496, 300.

Siderius, W. (Ed.), 1986. Land Evaluation for Land-use Planning and Conservation in Sloping Areas. ILRI Publication 40. International Institute for Land Reclamation and Improvement, Wageningen.

Smiles, D.E., White, I., Smith, C.J., 2000. Soil science education and society. Soil Sci. 165, 87–89.

Sojka, R.E., Upchurch, D.R., Borlaug, N.E., 2003. Quality soil management or soil quality management: performance versus semantics. Adv. Agron. 79, 1–68.

Sovacool, B.K., 2007. Solving the oil independence problem: is it possible? Energy Policy 35, 5505–5514.

Sovacool, B.K., Brown, M.A., 2010. Competing dimensions of energy security: an international perspective. Annu. Rev. Environ. Resour. 35, 77–108.

Stocking, M.A., 2003. Tropical soils and food security: the next 50 years. Science 302, 1356–1359.

Stockmann, U., Adams, M., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., de Courcelles, V., de, R., Singh, K., Wheeler, I., Abbott, L., Angers, D., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J., Lal, R., Lehmann, C.J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99.

Swift, M.J., Izac, A.M.N., van Noordwijk, M., 2004. Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agric. Ecosyst. Environ. 104, 113–134.

Thompson, P.B., 2011. The ethics of soil: stewardship, motivation, and moral framing. In: Sauer, T.J., Norman, J.M., Sivakumar, M.V.K. (Eds.), Sustaining Soil Productivity in Response to Global Climate Change: Science, Policy, and Ethics. John Wiley & Sons, pp. 31–42.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somervills, C., Williams, R., 2009. Beneficial biofuels — the food, energy, and environment trilemma. Science 325, 270–271.

Tugel, A.J., Herrick, J.E., Brown, J.R., Mausbach, M.J., Puckett, W., Hipple, K., 2005. Soil change, soil survey and natural resources decision making: a blueprint for action. Soil Sci. Soc. Am. J. 69, 738–747.

Turbé, A., De Toni, A., Benito, P., Lavelle, P., Lavelle, P., Ruiz, N., Van der Putten, W.H., Labouze, E., Mudgal, S., 2010. Soil biodiversity: functions, threats and tools for policy makers. Bio Intelligence Service, IRD, and NIOO, Report for European Commission, DG Environment.

UNDESA, 2012. International decade for action. Water for Life. 2005–2015. (http://www.un.org./waterforlifedecade/food_security.shtml (Accessed 25/10/2012)).

UNEP, 1997. World Atlas of Desertification. United Nations Publication.

Valesquez, E., Lavelle, P., Andrade, M., 2007. GISQ, a multifunctional indicator of soil quality. Soil Biol. Biochem. 39, 3066–3080.

van Bruggen, A.H.C., Semenov, A.M., 2000. In search of biological indicators for soil health and disease suppression. Appl. Soil Ecol. 15, 13–24.

Vera, I., Langlois, L., 2007. Energy indicators for sustainable development. Energy 32, 875–882.

Warkentin, B.P., Fletcher, H.F., 1977. Soil quality for intensive agriculture. Proceedings of the International Seminar on Soil Environment and Fertility Management. Intensive Agricultural Society Science Soil and Manure. National Institute of Agricultural Science, Tokyo, pp. 594–598.

Wilson, B.R., Growns, I., Lemon, J., 2008. Land-use effects on soil properties on the north-western slopes of New South Wales: implications for soil condition assessment. Aust. J. Soil Res. 46, 359–367.

World Health Organization, 2012. Trade, Foreign Policy, Diplomacy and Health: Food Security. (http://www.who.int/trade/glossary/story028/en/ (Accessed 25/10/2012)).

Zak, D.R., Holmes, W.E., White, D.C., Peacock, A.D., Tilman, D., 2003. Plant diversity, soil microbial communities, and ecosystem function: are there any links. Ecology 84, 2042–2050.