

Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils

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11

12 **Abstract**

13 Soils play a pivotal role in major global biogeochemical cycles (carbon, nutrient and water),
14 while hosting the largest diversity of organisms on land. Because of this, soils deliver
15 fundamental ecosystem services, and management to change a soil process in support of one
16 ecosystem service can either provide co-benefits to other services or can result in trade-offs.
17 In this critical review, we report the state-of-the-art understanding concerning the
18 biogeochemical cycles and biodiversity in soil, and relate these to the provisioning,
19 regulating, supporting and cultural ecosystem services which they underpin. We then outline
20 key knowledge gaps and research challenges, before providing recommendations for
21 management activities to support the continued delivery of ecosystem services from soils.

22

23 We conclude that although soils are complex, there are still knowledge gaps, and fundamental
24 research is still needed to better understand the relationships between different facets of soils
25 and the array of ecosystem services they underpin, enough is known to implement best
26 practices now. There is a tendency among soil scientists to dwell on the complexity and
27 knowledge gaps, rather than to focus on what we do know, and how this knowledge can be
28 put to use to improve the delivery of ecosystem services. A significant challenge is to find
29 effective ways to share knowledge with soil managers and policy makers, so that best
30 management can be implemented. A key element of this knowledge exchange must be to raise
31 awareness of the ecosystems services underpinned by soils, and thus the natural capital they

1 provide. We know enough to start moving in the right direction, while we conduct research to
2 fill in our knowledge gaps. The lasting legacy of the International Year of Soils in 2015
3 should be for soil scientists to work together with policy makers and land managers, to put
4 soils at the centre of environmental policy making and land management decisions.

5

6 **1 Introduction**

7 Soils play a critical role in delivering a variety of ecosystem services (Scholes and Scholes,
8 2013). Management aimed at improving a particular ecosystem service can either provide co-
9 benefits to other services or can result in trade-offs (Robinson et al., 2013). Examples of some
10 of the synergies and trade-offs (Smith et al., 2013) and the role of soils in supporting
11 ecosystem services, and their role in underpinning natural capital (Dominati et al., 2010;
12 Robinson et al., 2009, 2014) have recently been reviewed. The ability of soils to provide
13 services is principally conferred by two attributes: the range of biogeochemical processes that
14 occur in the soil; and the functionality of soil biodiversity. In the following sub-sections we
15 present the state-of-the-art understanding and knowledge gaps on carbon, nutrient and water
16 cycling in soil, and their role as a habitat for organisms and as a genetic pool. We clarify how
17 the biogeochemical processes provide regulating, provisioning and supporting services, and
18 the role of biodiversity (genetic diversity, functional diversity, and abundance and activity of
19 organisms) in supporting these services. These functions collectively confer soil health,
20 which is critical for the underpinning of cultural services, among other things. A range of soil
21 services have been identified including soil as a source of raw materials such as sand or clay,
22 soil as a surface for building infrastructure, soil as an archive for landscape development and
23 history of human soil use (e.g. Blum, 2002) but here we focus on those that map on to
24 ecosystem services listed in the Millenium Ecosystem Assessment (MA) (Millennium
25 Ecosystem Assessment, 2005).

26 The MA classified ecosystem services into supporting, regulating, provisioning and cultural
27 services, and this categorisation is widely used, and though the scheme was not designed to fit
28 all assessments (Fisher et al., 2009), it has been modified for use in national ecosystem
29 assessments (e.g. UKNEA, 2011). More recently, the Common International Classification of
30 Ecosystem Services (CICES; Haines-Young and Potschin, 2012) was developed to support
31 environmental accounting in the European Union and in the United Nations Statistical
32 Division (European Commission *et al.*, 2013; European Commission *et al.*, 2014). A major

1 difference between the MA and the CICES classification systems is that CICES does not
2 include supporting services (see below), which are treated as intermediate steps in the
3 delivery of final goods and services (Haines-Young and Potschin, 2012). In this review, we
4 include supporting services, since they are often referred to in the literature, while accepting
5 the CICES observation that supporting services are not of direct benefit of people, although
6 they are of great indirect benefit. The MA (Millennium Ecosystem Assessment, 2005;
7 supplemented by UKNEA, 2011 for supporting services) provides definitions and examples
8 of provisioning, regulating, supporting, and cultural services as follows:

9 **Provisioning services** are "physical products obtained from ecosystems" and include: food
10 (including wild-harvested seafood and game, cultivated crops, wild foods and spices); raw
11 materials (including timber, pulp, skins, animal and vegetable fibres, organic matter, fodder,
12 and fertilizer); genetic resources (including genes for crop improvement and health care);
13 freshwater; minerals; medicinal resources (including pharmaceuticals, chemical models, and
14 test and assay organisms); energy (hydropower, biomass feedstocks including biofuels, wood
15 and charcoal,); and ornamental resources (including fashion, handicraft, jewellery, pets,
16 worship, decoration and souvenirs like furs, feathers, ivory, orchids, butterflies, aquarium
17 fish, shells, etc.).

18 **Regulating services** are "Benefits obtained from the regulation of ecosystem processes" and
19 include: carbon sequestration and climate regulation; waste decomposition and detoxification;
20 pollutant immobilization and detoxification; purification of water and air; regulation of water
21 flow (including flood alleviation); and pest and disease control.

22 **Supporting services** are "Ecosystem services that are necessary for the production of all
23 other ecosystem services" and include: soil formation; nutrient cycling; water cycling,
24 primary production and habitat for biodiversity.

25 **Cultural services** are "Nonmaterial benefits people obtain from ecosystems through spiritual
26 enrichment, cognitive development, reflection, recreation, and aesthetic experiences" and
27 include: cultural (including use of nature as motif in books, film, painting, folklore, national
28 symbols, architectural, advertising, etc.); spiritual and historical (including use of nature for
29 religious or heritage value or sense of place); recreational experiences (including ecotourism,
30 outdoor sports, and recreation); science and education (including use of natural systems for
31 school excursions, and scientific discovery). Examples of cultural services underpinned by
32 soils are the terra preta soils of the Amazon basin, representing the historical cultural heritage

1 of the region before European settlers, histosols which are a vital component of peatland
2 landscapes, underpinning the landscape / amenity value of these valued wild areas, and soils
3 used as building material for traditional houses providing cultural heritage values, such as the
4 mud brick houses in Bam in Iran, and in Shibam in Yemen. This paper focusses on
5 biogeochemical cycling and soil biota, cultural services are not discussed further in detail in
6 this review.

7

8 [Figure 1 here]

9

10 Figure 1 summarises the ecosystem services underpinned by soils. In the following sections,
11 we examine the state-of-the-art understanding of carbon, nutrient and water cycles and
12 biodiversity in soils, and show how these underpin the provisioning, regulating, supporting
13 and cultural ecosystem services described above. We then discuss the knowledge gaps across
14 all of these areas, recommend key foci for future research, and present recommendations for
15 policies to support the continued delivery of these ecosystem services from soils.

16

17 **2 Soils and the Carbon Cycle**

18 *Soil C stocks:* Carbon (C) storage is an important ecosystem function of soils that has gained
19 increasing attention in recent years. Changes in soil C impacts on, and feedbacks with, the
20 Earth's climate system through emissions of CO₂ and CH₄, and storage of carbon removed
21 from the atmosphere during photosynthesis (climate regulation; Table 1). Soil organic matter
22 itself also confers multiple benefits for human society e.g. enhancing water purification and
23 water holding capacity, protecting against erosion risk, and enhancing food and fibre
24 provision through improved soil fertility (Table 1; Pan et al., 2013; 2014).

25

26 Soil is an important C reservoir that contains more C (at least 1500-2400 Pg C) than the
27 atmosphere (590 Pg C) and terrestrial vegetation (350-550 Pg C), combined (Schlesinger and
28 Bernhardt, 2013; Ciais et al., 2013), and an increase in soil C storage can reduce atmospheric
29 CO₂ concentrations (Table 1; Whitmore et al., 2014). All three reservoirs of C are in constant
30 exchange but with various turnover times, with soil as the largest active terrestrial reservoir in
31 the global C cycle (Lal, 2008). Carbon storage in soils occur both in organic and inorganic

1 form. Organic C stocks in the world's soils have been estimated to comprise 1500 Pg of C to
2 1 m depth and 2500 Pg to 2m (Bajes, 1996). Recent studies showed that the soil C pool to 1 m
3 depth may be even greater and could account for as much as 2000 Pg. These higher values are
4 mainly based on increased estimates of the C stored in boreal soils under permafrost
5 conditions (Tarnocai et al., 2009), in which decomposition is inhibited by low temperature,
6 and lack of oxygen and low pH in waterlogged soils, e.g. peats (Smith et al., 2010). Although
7 the highest C concentrations are found in the top 30 cm of soil, the major proportion of total C
8 stock is present below 30 cm depth (Batjes, 1996). In the northern circumpolar permafrost
9 region, at least 61% of the total soil C is stored below 30 cm depth (Tarnocai et al., 2009).
10 Peatlands are particularly important components of the global soil carbon store, covering only
11 3% of the land area, but containing around 500 Pg C in organic rich deposits ranging from
12 0.5-8 m deep (Gorham, 1991; Yu, 2012) with storage in deeper layers as yet unquantified.

13
14 In arid and semi-arid soils, significant inorganic C can be present as carbonate minerals
15 (typically Ca/MgCO₃, called 'calcrete' or 'caliche' in various parts of the world), formed from
16 the reaction of bicarbonate (derived from CO₂ in the soil) with free base cations, which can
17 then be precipitated in subsoil layers (Nordt et al., 2000). Also soils derived from carbonate-
18 containing parent material (e.g. limestone) can have significant amounts of inorganic C. The
19 inorganic C pool globally is large, estimated to be ~750 Pg C to a depth of 1m (Batjes, 1996).
20 However, in most cases, changes in inorganic C stocks are slow and not amenable to
21 traditional soil management practices, and do not play a significant role in terms of most
22 ecosystem services (though a major exception is the geoengineering proposal to add finely-
23 ground silicate minerals to soils, which will then weather to carbonates, taking up CO₂ in the
24 process; Köhler et al., 2010). Thus, further discussion of soil C in this review will focus on
25 soil organic C.

26
27 The net balance of soil C depends on the C inputs to soils relative to C losses. Losses can
28 occur *via* mineralization (i.e. decomposition), leaching of dissolved C and carbonate
29 weathering (Smith, 2012; Schlesinger and Bernhardt, 2013). Thus the soil organic C stock
30 may either increase or decrease in response to changes in climate and land use practices
31 (Smith et al., 2015). Furthermore, rates of SOC stock change in different parts of the profile
32 can vary for different soils and types of perturbation, because some portion of the C stored in
33 soil mainly in top soil turns over rapidly, while other soil C fractions can have a long

1 residence time (von Lützow et al., 2008; Rumpel and Kögel-Knabner, 2011). The
2 accumulation of stabilised C with long residence times in deep soil horizons may be due to
3 continuous transport, temporary immobilisation and microbial processing of dissolved organic
4 matter within the soil profile (Kalbitz and Kaiser, 2012) and/or efficient stabilisation of root-
5 derived organic matter within the soil matrix (Rasse et al., 2005). The process of soil
6 formation – i.e. the development of depth, horizons and specific properties - is itself a
7 supporting service (Table 1).

8

9 High SOC content also improves other chemical and physical soil properties, such as nutrient
10 storage (supporting service), water holding capacity (supporting and regulating service),
11 aggregation and sorption of organic or inorganic pollutants (regulating service). Carbon
12 sequestration in soils may therefore be a cost-effective and environmentally friendly way, not
13 only to store C for climate regulation, but also to enhance other ecosystem services derived
14 from soil, such as agricultural production, clean water supply, and biodiversity (Table 1; Pan
15 et al., 2013) by improving soil organic matter (SOM) content and thereby soil quality (Lal,
16 2004). Moreover, processes which improve SOM may themselves provide services, e.g. use
17 of cover crops which can provide provisioning or water regulation services while improving
18 soil C (Table 1). SOM or soil carbon are widely-used proxy variables for soil health (e.g.
19 Kibblewhite et al., 2008).

20

21 *C cycling*: Carbon enters the soil as aboveground or belowground plant litter and exudates. C
22 input is not homogenous within the soil profile. Whereas topsoil receives higher amounts of
23 aboveground litter, subsoil C originates from root C as well as dissolved C, transported down
24 the soil profile. Root C has a greater likelihood of being preserved in soil compared to shoot
25 C, and was therefore hypothesised to account for most of the SOC (Rasse et al., 2005). The
26 majority of plant litter compounds pass through and are modified by the soil biota. Thus SOM
27 is composed of plant litter compounds as well as microbial and, to a smaller extent, faunal
28 decomposition products (Paul, 2014). It is a complex biogeochemical mixture comprising
29 molecules derived from organic material in all stages of decomposition. Some organic matter
30 compounds, including microbial decomposition products, may be stabilised for centuries to
31 millennia by binding to soil minerals or by physical occlusion into micro-aggregates (von
32 Lützow et al., 2008), for example with iron oxyhydrates (Zhou et al., 2009), or through
33 protection by occlusion within soil aggregates (Dungait et al., 2012). The inherent chemical

1 recalcitrance of some plant litter compounds (e.g. lignin) has a minor influence on their
2 longevity in soil (Thevenot et al., 2010) whereas the location of SOM within the soil matrix
3 has a much stronger control on its turnover (Chabbi et al., 2009; Dungait et al., 2012).
4 Mineral-associated SOM is predominantly composed of microbial products (Miltner et al.,
5 2012). Therefore, microbial use efficiency (Liu et al., 2011) of plant inputs largely determines
6 SOM stabilisation through interaction with the mineral phase (Cotrufo et al., 2013), in
7 addition to the environmental controls discussed elsewhere in this section. In peatlands,
8 organic matter is stabilised by high water tables that slow down biological activity and
9 decomposition. SOM is mineralized to carbon dioxide (CO₂) in aerobic environments, or
10 reduced to methane (CH₄) in anaerobic environments. Soil CO₂ efflux, resulting from SOM
11 mineralization, and from rhizosphere respiration and inorganic C weathering, is the largest
12 terrestrial flux of CO₂ to the atmosphere (~60 Pg C; the sink of carbon on the other hand
13 contributes to the climate regulation service; Smith 2004). This flux is an order of magnitude
14 larger than anthropogenic CO₂ emissions due to fossil fuel burning and land use change (1.1
15 Pg C/yr, Ciais et al 2013). Under anaerobic conditions, CH₄ is formed by methanogenic
16 microorganisms. A proportion of this CH₄ is oxidised to CO₂ by methanotrophic
17 microorganisms, but a proportion can be emitted from the soil surface (Reay et al., 2010).
18 Since CH₄ is many times more potent as a greenhouse gas than CO₂ on a per-molecule of per-
19 mass basis (Ciais et al., 2013), soil CH₄ emissions and their mitigation play an important role
20 in climate regulation (Table 1).

21
22 Fire may affect many ecosystem services, including C sequestration. For fires in natural
23 ecosystems, a decrease in soil C storage is often observed initially, but through positive
24 effects on plant growth, as well as input of very stable pyrogenic C, C storage may increase at
25 longer timescales (Knicker, 2007). An additional long-term C pool in many soils is
26 pyrogenic-carbon (PyC), formed from partially combusted (i.e. pyrolysed) biomass during
27 wildfires or other combustion processes (Schmidt and Noack, 2000). Globally, soils are
28 estimated to contain between 54 and 109 Pg PyC (Bird et al., 2015). Some of this PyC has a
29 highly condensed aromatic structure that retards microbial decay, and can thus persist in soils
30 for relatively long periods (Sing et al., 2012). Soil amended with industrially produced PyC
31 (biochar) as a climate mitigation technique often shows no increase in soil respiration despite
32 the additional carbon, the reduced ecosystem carbon turnover results in increased soil carbon
33 storage (Stewart et al., 2013). PyC additions to soil affect regulating ecosystem services, such

1 as C sequestration, nutrient cycling and adsorption of contaminants. However, PyC
2 properties, and as result their effect on ecosystem services, may be strongly dependent on fire
3 conditions.

4
5 *Factors influencing soil C storage:* Fundamentally, the amount of C stored in a given soil is
6 determined by the balance of C entering the soil, mainly *via* plant production but also through
7 manures or amendments such as organic sludge or biochar, and C leaving the soil through
8 mineralization (as CO₂), driven by microbial processes, and to a lesser extent leaching out of
9 the soil of dissolved carbon and carbonate weathering. Locally, C can be lost or gained
10 through soil erosion or deposition, leading to a redistribution of soil C, at landscape and
11 regional scales (van Oost et al., 2007).

12
13 Consequently, the main controls on soil C storage are the amount and type of organic matter
14 inputs, the efficiency by which this is used by microbes, and the capacity of the soil to retain
15 it by physical or chemical stabilization (Cotrufo et al., 2013). In most natural and agricultural
16 ecosystems, plant productivity and subsequent death and senescence of biomass provide the
17 input of organic C to the soil system (Table 1). Thus, higher levels of plant residue inputs will
18 tend to support higher soil organic carbon stocks, and *vice versa* (Paustian et al., 1997),
19 though this does not continue indefinitely (Zvomuya et al., 2008). Plants also affect soil C
20 cycling by their specific mycorrhizal associations (Brzostek et al., 2015). Shifts in specific
21 mycorrhizal associations affect SOM storage by contributing to both SOM formation and
22 decomposition. Ectomycorrhizal turnover is a dominant process of SOM formation
23 (Godbold et al., 2006), possibly due to the more recalcitrant nature of the chitin in fungal
24 tissues, compared to the cellulose and lignin in plant residues. In arbuscular mycorrhizal
25 fungi, it has been suggested that glomalin, a highly resistant glycoprotein, has an active role in
26 aggregate formation and SOM stocks (Rillig, 2004). Symbiotic mycorrhizal fungi can also
27 directly impact the turnover of organic matter by the production of exo-enzymes (Averill et
28 al., 2014; Finzi et al., 2015).

29
30 In many regions of the world SOM accumulates because of inhibition of microbial SOM
31 decomposition, due to cold, dry or anoxic conditions (Trumbore, 2009). In general, when
32 water is not limiting, higher soil temperatures increase the rate of microbial decomposition of
33 organic matter. Thus soil temperature is a major control of SOM storage in soil C cycle

1 models (Peltoniemi et al., 2007). The temperature sensitivity of SOM decomposition is not,
2 however, as straight-forward as represented in most models, but varies between the many
3 different forms of chemical and physical protection of organic matter in soil (Conant et al.
4 2011; Zheng et al., 2012). Water influences soil C storage through several processes. Moist,
5 but well-aerated, soils are optimal for microbial activity and decomposition rates decrease as
6 soils become drier. However, flooded (saturated) soils have lower rates of organic matter
7 decay due to restricted aeration and thus often have very high amounts of soil C (e.g. peat
8 soils). High precipitation may also lead to C transport down the soil profile as dissolved
9 and/or particulate organic matter, as well as lateral transport through soil erosion and
10 deposition. During dry periods, SOM decomposition is decreased, but after rewetting there
11 may be an accelerated pulse of CO₂ emission in aerobic soils (Borken and Matzner, 2008) ,
12 whereas drought and lowering water tables may increase decomposition in naturally
13 anaerobic peats (Freeman et al, 2001; Clark et al., 2012). However, the effect of drought is
14 not only direct *via* soil microbial activity. There are feedback loops concerning drought and C
15 storage *via* plant activities, such as litter input and rhizodeposition. Drought was found to
16 affect plant litter composition (Sanaullah et al., 2014), plant C flow and root exudation
17 (Sanaullah et al., 2012), as well as the resulting enzyme activities in the rhizosphere
18 (Sanaullah et al., 2011).

19

20 C cycling in soils is strongly linked to the cycling of N and P. Since the C:N:P stoichiometry
21 in SOM is generally lower than in plant material - i.e. there is more N and P per unit C: C
22 generally accumulates in aerobic soil where nutrients are not limiting (Alberti et al., 2014).
23 Nevertheless, increase in organic C is often accompanied by increased N resource use
24 efficiency in croplands (Pan et al. 2009), especially when SOC is increased with biochar
25 (Huang, et al., 2013). In nutrient limited peatlands, inputs of nitrogen and/or phosphorus
26 within the tolerance levels of sensitive plant species have increased rates of carbon
27 accumulation (Aerts et al., 1992; Turunen et al., 2004; Olid et al., 2014). The relationship
28 between nutrients and C cycling is not straight forward, since nutrients are also needed by soil
29 microbes to degrade SOM. Thus nutrient addition can either decrease or increase C storage,
30 depending on the initial SOM stoichiometry, the ability of the soil minerals to stabilize
31 microbial products of decomposition and the simultaneous effects on plant productivity and
32 organic matter inputs to soils.

33

1 The amount and type of clay particles (and to a lesser extent silt particles) are the major factor
2 controlling the quantity and composition of soil C (Sollins *et al.* 1996, von Lützow *et al.*
3 2006). Clays are mainly sheet-like crystals of silicon and aluminium, known as
4 phyllosilicates, often located as skins coating soil aggregates. In clay-rich soils, higher
5 organic matter content and a greater concentration of O-alkyl C derived from polysaccharides
6 may be expected compared to sandy soil, which are characterised by lower C contents and
7 high concentrations of alkyl C (Rumpel and Kögel-Knabner, 2011). Aliphatic material may be
8 responsible for the hydrophobicity of soils, which can lead to reduced microbial accessibility
9 and therefore increased C storage (Lorenz *et al.*, 2007). Many of the OM-matrix interactions
10 are driven by expandable and non- expandable phyllosilicates, which interact with organic
11 compounds through their large surface areas, micro pores and micro aggregation, particularly
12 in acid soils. In neutral and calcareous soils, polyvalent cations (especially Ca^{2+}) predominate
13 in the interaction mechanism, forming bridges between the largely negatively charged SOM
14 and negatively charged phyllosilicates (Cotrufo *et al.*, 2013). Short order silicates, like
15 allophane, provide some of the strongest organo-mineral interactions and stabilize both
16 proteins and carbohydrate monomers, though their occurrence is very geographically
17 restricted (Buurman *et al.* 2007; Dümig *et al.* 2012; Mikutta and Kaiser 2011). Pedogenic
18 oxides (for example iron oxyhydrates in rice paddies) usually act as coating of soil mineral
19 particles and stabilize carbon, contributing to a higher C storage and stability than other soils
20 (Song *et al.*, 2012).

21
22 Bioturbation (the mixing of soil by organisms) may further influence the amount as well as
23 the chemical nature of soil C. It greatly influences the heterogeneity of soils by creating
24 hotspots of carbon and biological activity. On biologically active sites, incorporation and
25 transformation of organic compounds into soil is usually enhanced, leading to more organo-
26 mineral interactions and increased C storage (Wilkinson *et al.*, 2009).

27
28 Microbial decomposition of SOM may be stimulated by the input of labile (easily
29 decomposed) organic matter, through the priming effect (Jenkinson *et al.* 1971). Positive
30 priming refers to greater mineralisation of otherwise stable C through shifts in microbial
31 community composition and activity (Fontaine *et al.*, 2003). However, in some cases the
32 addition of organic matter to soil may also impede mineralisation of native SOM (negative
33 priming effect), thereby protecting SOM from its decomposition. Plant communities (Table 1)

1 are the main controlling factors of these processes because they influence organic matter input
2 and microbial activity by their effects on soil water, labile C input, pH and nutrient cycling
3 (Kuzyakov et al. 2000).

4

5 By storing and cycling C, nutrients and water, soils provide supporting services like soil
6 formation, nutrient retention and water retention, which underpin both primary production
7 and landscape hydrology (the processes which deliver provisioning services such as food,
8 fibre and water; Table 1), in addition to the regulating services such as climate regulation
9 already discussed (Figure 1). To assure that soils continue to provide these key services soil
10 will require to be managed both for C preservation – thus mitigating climate change – while
11 simultaneously permitting continued SOM recycling (Table 1). Janzen (2006) pointed to this
12 dilemma, that there is a trade-off between improved soil fertility to support the provisioning
13 services of food/timber production and the regulating service of soil carbon sequestration
14 aiding climate regulation. Despite knowledge on which practices are likely to lead to
15 improved SOC status, better understanding of the controls on SOM distribution, stabilisation
16 and turnover will help to better target these practices. This will be an important contribution
17 to the mitigation of greenhouse gases, while assuring decomposition and with it the cycling of
18 nutrients necessary to support food production. Table 1 summarises management actions
19 affecting the soil carbon cycle and their impacts on ecosystem services.

20

21 [Table 1 here]

22

23 **3 Soils and Nutrient Cycles**

24 Soils support primary production among other services, which in turn delivers the
25 provisioning services of food and fibre production (Table 2). As such, soils are vital to
26 humanity since they provide essential nutrients, such as nitrogen (N), phosphorous (P) and
27 potassium (K) and many trace elements that support biomass production, which is essential
28 for supply of human and animal food, for energy and fibre production and (future) feedstock
29 for the chemical industry (Table 2). Since the 1950s, higher biomass production and yield
30 increases have been supported through fertilizers derived from mined minerals or industrially
31 synthesised (Figure 2). Intensification of agricultural practices and land use has in many
32 regions resulted in a decline in the content of organic matter in agricultural, arable soils

1 (Tbale 2; Matson et al., 1997; Smith et al., 2015). In some areas, extensive use of mineral
2 fertilizers has led to atmospheric pollution, greenhouse gas emissions (e.g. N₂O, very
3 important for climate regulation), water eutrophication, and human health risks (Galloway et
4 al., 2008), thereby negatively affecting the regulating services of soil, air and water quality
5 (Table 2; Smith et al., 2013). During the 21st century, it is likely that the human population
6 and demand for food, feed and energy will rise. In order to sustain biomass production in the
7 future, and to avoid negative environmental impacts, fertile soils need to be preserved and soil
8 fertility needs to be restored where lost. This can be done through both the recycling and
9 accumulation of sufficient amounts of organic matter in soils (Janzen, 2006), through a
10 combination of plant production and targeted additions of organic and mineral amendments to
11 soils (see section 2).

12 The soil function “fertility” refers to the ability of soil to support and sustain plant growth;
13 which relates to making available N, P, other nutrients, water and oxygen for root uptake.
14 This is facilitated by i) their storage in soil organic matter, ii) nutrient recycling from organic
15 to plant available mineral forms, and iii) physical – chemical processes that control their
16 sorption, availability, displacement and eventual losses to the atmosphere and water (Table 2).
17 Managed soils are a highly dynamic system and it is this very dynamism that makes the soil
18 work and supply ecosystem services to humans. Overall, the fertility and functioning of soils
19 strongly depend on interactions between the soil mineral matrix, plants and microbes; these
20 are responsible for both building and decomposing SOM, and therefore for the preservation
21 and availability of nutrients in soils (Cotrufo et al., 2013). To sustain this service, the cycling
22 of nutrients in soils must be preserved (Table 2).

23

24 [Figure 2 here]

25

26 After carbon, N is the most abundant nutrient in all forms of life, since it is contained in
27 proteins, nucleic acids and other compounds (Galloway et al., 2008). Humans and animals
28 ultimately acquire their N from plants, which on land is mostly taken up in mineral form (i.e.,
29 NH₄⁺ and NO₃⁻) from the soil. The parent material of soils does not contain significant
30 amounts of N (most other nutrients such as P largely originate from the parent material). New
31 N mostly enters the soil through the fixation of atmospheric N₂ by a specialized group of
32 microorganisms. However, the largest flux of N *within* the soils is generated through the

1 continuous recycling of N internal to the plant-soil system: soil mineral N is taken up by the
2 plant, it is fixed into biomass, and eventually N returns in the form of plant debris to the soil.
3 Here microorganisms decompose it, mineralizing part of the N and making it newly available
4 for plant growth, while transforming the other part into SOM, which ultimately is the largest
5 stock of stable N in soil. Generally, N cycles tightly in the system with minimal losses.
6 Nitrogen is lost from the soil to the water system by leaching and to the atmosphere by gas
7 efflux (NH_4 , N_2O and N_2). In most terrestrial natural ecosystems, N availability limits
8 productivity. Through the cultivation of N_2 fixing crops, the production and application of
9 mineral N fertilizer, increasing application of animal manure from livestock and bio-wastes,
10 and the unintentional deposition of atmospheric reactive N (ultimately derived from
11 industrial-era human activities), humans have applied twice as much reactive N to soils as the
12 N introduced by natural processes, significantly increasing biomass production on land
13 (Vitousek and Mason, 1993; Erisman et al., 2008). In some regions of the world, mineral
14 fertilizer is applied in excess of plant requirement, but in other regions, in particular in Sub-
15 Saharan Africa where economic constraints limit the use of fertilizers, productivity is strongly
16 limited by soil available N and other nutrients, notably P and K (N and P; Fig. 3).

17 Phosphorus derived from parent material, through weathering, cycles internally in the plant -
18 soil system between biochemical molecules (e.g. nucleic acid, phospholipids, etc.) and
19 mineral forms after decomposition (e.g. H_3PO_4). In soils, P is among the most limiting of
20 nutrients, since it occurs in small amounts and is only available to plants in its dissolved ionic
21 forms, which promptly react with calcium, iron and aluminium cations to form highly
22 insoluble compounds. Largely in these forms, P is lost to the aquatic system through erosion
23 and surface runoff. Losses may also occur in dissolved form, for instance *via* sub-surface flow
24 and groundwater (McDowell et al., 2015). An important form of loss is in the export of
25 organic P in agricultural products. Due to widespread agricultural P deficiencies,, humans
26 started to mine 'primary' P from guano or rock phosphate deposits and added it to soils in the
27 form of mineral fertilizer (Figure 2). This external input has led to positive agronomic P
28 balances (McDonald et al., 2011) and excesses of P and N in many regions (West et al., 2014;
29 Figure 3). There are large variations across the world, with high surpluses in the USA, Europe
30 and Asia, and deficits in Russia, Africa and South-America (Figure 3). Since plant P uptake is
31 a relatively inefficient process with roughly 60 % of the total P input to soils not taken up in
32 the short term, a threefold increase in the export of P to water bodies has been estimated, with
33 significant impacts on water quality (Bennett et al., 2001).

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[Figure 3 here]

Clearly, management practices need to be implemented that sustain, restore or increase soil fertility and biomass production by promoting the accrual of SOM and nutrient recycling, applying balanced C amendments and fertilization of N, P and other nutrients to meet plant and soil requirements, while limiting the addition of excess fertilizer and retaining nutrients in the soil-plant system (Table 2). Carbon, N and P cycling in soils is coupled by tight stoichiometric relationships (e.g. relatively fixed C:N:P in plants and microorganisms; Güsewell, 2004), thus their management needs to be studied in concert. Nutrient management has been extensively studied, with the aim of identifying and proposing management practices (e.g. precision agriculture) that improve nutrient use efficiency and productivity, and reduce potentially harmful losses to the environment (Table 2; van Groenigen *et al.* 2010; Venterea *et al.* 2011). Yet, our ability to predict the ecosystem response to balanced fertilization is still limited, and effectiveness and reliability would benefit from continued monitoring of efforts. Further benefits are anticipated from improved plant varieties with root morphologies that have better capacity to extract P from soils or use it more efficiently, perhaps in concert with mycorrhizal symbionts. Fertilization with nutrients other than N and P has been less well explored within the realm of understanding soil organic matter responses to agricultural C inputs and the potential to restore and increase soil organic matter (e.g. Lugato *et al.*, 2006). Hence, we stress the importance of an integrated approach to nutrient management, which supports plant productivity while preserving or enhancing SOM stocks, and reducing nutrient losses to the atmosphere or water resources. Several issues exist where prediction and optimization of performance would benefit from relevant and continued data acquisition for the range of climate and environmental and agro-ecological conditions. Table 2 summarises some management actions affecting soil nutrient cycles and their impacts on ecosystem services.

[Table 2 here]

1 **4 Soils and the Water Cycle**

2 Soils provide important ecosystem services through their control on the water cycle. These
3 services include provisioning services of food and water security, regulating services
4 associated with moderation and purification of water flows, and contribute to the cultural
5 services of landscapes / water bodies that meet recreation and aesthetic values (Table 3;
6 Dymond, 2014). At the pedon to hillslope scale, water stored in soil is used for
7 evapotranspiration and plant growth that supplies food, stabilizes the land surface to prevent
8 erosion and regulates nutrient and contaminant flow. At a catchment and basin scale, the
9 capacity of the soil to infiltrate water attenuates stream and river flows and can prevent
10 flooding, while water that percolates through soil can replenish groundwater that can maintain
11 water supplies and sustain surface water ecosystems while promoting a continued flow during
12 periods of reduced precipitation (Guswa et al., 2014).

13 The soil functions of accepting, storing, transmitting and cleaning of water shown in Table 3
14 are inter-related. Soil water storage depends on the rate of infiltration into the soil relative to
15 the rate of precipitation. Soil hydraulic conductivity redistributes water within and through the
16 soil profile. The infiltration rate and hydraulic conductivity both depend on the water stored in
17 the soil. The initially high rate of infiltration into dry soil declines as the soil water content
18 increases and water replaces air in the pore space. Conversely, hydraulic conductivity
19 increases with soil moisture content as a greater proportion of the pores are transmitting
20 water. Water content and transmission times are also important to the filtering function of soil
21 because contact with soil surfaces and residence time in soil are important controls on
22 contaminant supply and removal (McDowell and Srinivasan, 2009).

23 The quantity of water which a soil can store depends on the thickness of the soil layer, its
24 porosity and soil matrix-water physical interactions. The latter are expressed as a water
25 retention curve, the relationship between the soil water content and the forces holding it in
26 place. The porosity and water retention curve are in turn influenced primarily by the particle
27 size distribution and the soil bulk density, but also the amount of SOM and the macropores
28 created by biotic activity (Kirkham, 2014).

29

30 [Table 3 here]

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1 Optimum growth of most plants occurs when roots can access both oxygen and water in the
2 soil. The soil must therefore infiltrate water, drain quickly from saturation to allow air to
3 reach plant roots, and retain and redistribute water for plant use. An ideal soil for plant
4 production depends on the climatic conditions. Soil structural stability and porosity are also
5 important for the infiltration of water into soil. In addition to soil texture, organic matter
6 improves soil aggregate stability (Das et al., 2014). While plant growth and surface mulches
7 can help protect the soil surface, a stable, well-aggregated soil structure that resists surface
8 sealing and continues to infiltrate water during intense rainfall events will decrease the
9 potential for downstream flooding resulting from rapid overland flow. Porosity (especially
10 macropores of a diameter $\geq 75 \mu\text{m}$) controls transmission of water through the soil. In
11 addition to total porosity, the continuity and structure of the pore network are as important to
12 these functions as they are in filtering out contaminants in flow. Furthermore, the soil must
13 support biota that will degrade the compounds of interest or have sorption sites available to
14 retain the chemical species. Soil organic matter is important for these roles and together with
15 mineral soil (especially the clay fraction) provides sorption sites (Bolan et al., 2011). Flow
16 through macropores, which bypass the soil matrix where biota and sorption sites are generally
17 located, can quickly transmit water and contaminants through the soil to groundwater or
18 artificial drains, but for filtering purposes a more tortuous route through the soil matrix is
19 more effective (McDowell et al., 2008). There are multiple other links between soil biota and
20 soil water, with water potential in particular having a pivotal role on the structure, growth and
21 activity of the soil microbial community (Parr et al., 1981).

22

23 Management of soil alters the ecosystem services provided by water (Table 4). Soil
24 conservation and sustainable management practices to combat desertification help to retain
25 soil organic matter, structural stability, infiltration and profile water holding capacity. The
26 promotion of soil as a C sink to offset greenhouse gas emissions generally helps to maintain
27 or improve soil hydrological functions as well. Deforestation, overgrazing and excessive
28 tillage of fragile lands, however, will lead to soil structural deterioration and a loss of
29 infiltration, water retention and surface water quality (Table 4; Steinfeld et al., 2006).
30 Anthropogenic modifications to the water cycle can aid soil function. In dry regimes,
31 inadequate soil moisture can be mitigated through supplementary irrigation, and where
32 waterlogging occurs it can be relieved by land drainage. However, irrigation and drainage can

1 have consequences for water regulation services. Irrigation that enables a shift to intensive
2 land use can increase the contaminant load of runoff and drainage (Table 4; McDowell et al.,
3 2011). Furthermore, drainage of wetland soils has been shown to reduce water and
4 contaminant storage capacity in the landscape and can increase the potential for downstream
5 flooding, and increase the potential for GHG emissions due to the rapid decomposition of
6 SOC in soil and dissolved organic C in drainage water (IPCC, 2013). The removal of surface
7 or groundwater for irrigation disrupts the natural water cycle and may stress downstream
8 ecosystems and communities. Irrigation of agricultural lands accounts for about 70% of
9 ground and surface water withdrawals, and in some regions competition for water resources is
10 forcing irrigators to tap unsustainable sources. Irrigation with wastewater may conserve fresh
11 water resources, but the fate of water-borne contaminants in soil and crops is a potential
12 concern (Sato et al., 2013).

13

14 [Table 4 here]

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16 **5 Soils as a habitat for organisms and as a genetic resource**

17 Soils represent a physically and chemically complex and heterogeneous habitat supporting
18 high diversity of microbial and faunal taxa. For example, 10 g of soil contains about 10^{10}
19 bacterial cells, representing more than 10^6 species (Gans et al., 2005). Up to 360 000 species
20 of animals live predominantly in the soil – a large fraction of all animal species (Decaëns et
21 al., 2006). These complex communities of organisms play critical roles in sustaining soil and
22 wider ecosystem functioning, thus conferring a multitude of benefits to global cycles and
23 human sustainability. Specifically, soil biodiversity contributes to food and fibre production,
24 and is an important regulator of other soil services including greenhouse gas emissions, water
25 purification (Table 5; Bodelier, 2011) and supporting services such as nutrient cycling. Stocks
26 of soil biodiversity represent an important biological and genetic resource for
27 biotechnological exploitation. Previous methodological challenges in characterizing soil
28 biodiversity are now being overcome through the use of molecular technologies, and currently
29 significant progress is being made in opening the “black box” of soil biodiversity (Allison and
30 Martiny, 2008) with respect to providing fundamental information on normal operating ranges
31 of the biodiversity under different soil, climatic and land use scenarios. Addressing these
32 knowledge gaps is of fundamental importance, firstly as a prelude to understanding wider soil

1 processes, but also to better inform the likely consequences of land use or climatic change on
2 both biodiversity and soil ecosystem services.

3 The development of molecular technologies has led to a surge in studies characterizing soil
4 biodiversity at different scales – from large landscape scale surveys to specific, locally-
5 focused studies using manipulation, or contrasting of specific land uses. The large-scale
6 surveys yield the broader picture, and conclusions are emerging identifying the importance of
7 soil parameters in shaping the biodiversity of soil communities (Fierer and Jackson, 2006). In
8 essence, the same geological, climatic and biotic parameters which ultimately dictate the
9 supporting service of soil formation, are also implicated in shaping the communities of soil
10 biota, thus regulating the spatial structure of soil communities observed over large areas
11 (Griffiths et al., 2011). Locally focused experimentation typically reveals more specific
12 changes with respect to local land use or climate. Most studies have focused on assessing one
13 component of soil diversity. Next-generation high throughput sequencing now allows the
14 analyses of “whole soil foodwebs”, permitting a thorough interrogation of trophic and co-
15 occurrence interaction networks. The challenge is to consolidate both approaches at various
16 scales, to understand the differing susceptibility of global soil biomes to change.

17 It is essential to link these new biodiversity measures to specific soil functions in order to
18 understand the pivotal roles of soil organisms in mediating soil services. The development of
19 *in situ* stable isotope tracer methods (e.g. Radajewski et al., 2000) to link substrate use to the
20 identified active members serves to clarify the physiological activity of these organisms.
21 Additionally, whole genome shotgun metagenomic sequencing is now becoming an
22 increasingly cost effective approach to assessing the biodiversity of functional genes in soils
23 (Fierer et al., 2013), potentially allowing for a trait-based rather than taxon-based approach to
24 understanding soil biodiversity, akin to recent approaches applied to larger and more readily
25 functionally understood organisms above-ground. It is becoming increasingly apparent that
26 functionality and biodiversity co-vary with other environmental parameters. Thus
27 manipulative experimentation is required to determine the fundamental roles of soil
28 biodiversity *versus* other co-varying factors in driving soil functionality. Table 5 summarises
29 management actions affecting the soil biota and their impacts on ecosystem services.

30

31 [Table 5 here]

32

6 Knowledge gaps and research needs concerning soil carbon, nutrient and water cycles, and the role of soil biodiversity

Soil carbon cycle: Substantial progress has been made in recent years towards more fundamental understanding of the processes controlling soil C storage and in improving and deploying predictive models of soil C dynamics that can guide decision makers and inform policy. However, it is equally true that many new (and some old) gaps in our knowledge have been identified and research needs articulation. New research on soil C dynamics has been driven in part by increasing awareness of (1) the importance of small scale variability for microbial C turnover (Vogel et al., 2014), (2) interactions between the C cycle with other biogeochemical cycles (Gärdenäs et al., 2011) and (3) the importance of soil C, not only at the field scale, but at regional to global scales (Todd-Brown et al. 2013). The most cited gaps in basic knowledge include plant effects on SOM storage and turnover, controls on microbial efficiency of organic matter processing, including biodiversity, association/separation of organic matter and decomposing microbial communities in the mineral soil matrix (Bardgett et al., 2008), role of soil fauna in controlling carbon storage and cycling, dynamics of dissolved organic carbon and its role in determining C storage and decomposition (Moore et al., 2031; Butman et al., 2014), black C stabilization and interactions of black C including biochar with native soil C and mineral nutrients, and the role of soil erosion in the global C cycle (Quinton et al., 2010). For predictive modelling and assessment, most frequently cited knowledge gaps are: closer correspondence of measured and modelled SOM fractions (Zimmermann et al., 2007), improved modelling of C in subsurface soil layers, distributed soil C observational and monitoring networks for model validation, more realistic and spatially-resolved representation of soil C in global-scale models, and the response to climatic extremes (Reichstein et al., 2013).

Soil nutrient cycles: In the second half of the 20th century, higher biomass yields were supported by higher use of fertilizer (N, P) inputs. Today, at the beginning of the 21st century, this is not considered sustainable. Alternatives are needed that will use inherent soil fertility and improved resource use efficiencies, and to prevent losses of N and P. Examples in agriculture include ecological intensification and new crop varieties with improved ability to extract P and use from soils. At the food system level, more effective nutrient management would benefit from a focus on a “5R strategy”: (1) Re-align P and N inputs, (2) Re-duce P and N losses to minimize eutrophication impacts, (3) Re-cycle the P and N in bio - resources,

1 (4) Re-cover P (and N) from wastes into fertilizer, and (5) Re-define use and use-efficiency of
2 N and P in the food chain including diets and regional and spatial variability (e.g. Snyder et
3 al., 2014).

4 *Soil water*: The soil management practices that maintain the ecosystem services of food and
5 water provision, flow regulation, water purification, and aesthetic value within the soil and
6 water cycle are well known. However, their application is not universal and poor management
7 leads to a loss of function. Under scenarios of increased climatic variability with more
8 extremes of precipitation and increased severity of droughts, soil functions will be stressed
9 and the level of good soil management will be required to improve (Walthall et al., 2012).
10 Research into these interactions, and future-proofing of current good practice is required.

11 *Soil biota*: Despite recent advances in knowledge regarding stocks and changes in soil
12 biodiversity, global scale syntheses are still largely absent. Indeed many of these highly
13 pertinent issues were raised more than 20 years ago (Furusaka, 1993), and to date none of
14 these factors have been unravelled fully. Key barriers to syntheses are the lack of concerted
15 soil surveys addressing multiple functions with standardized methodologies. New
16 technologies for soil biodiversity assessment generate large datasets of gene sequences which
17 are typically archived in publicly accessible databases. The adoption of such approaches for
18 soil function measurements alongside deployment of agreed standard operating procedures
19 (e.g. as developed in recent EU funded EcoFINDERS project), could serve to address these
20 gaps. Ultimately, new methods are revealing the high sensitivity of change of soil biological
21 and genetic resources from threats such as management, and we now need to recognize the
22 distinct types of organisms found in different soils globally, and understand their functional
23 roles in order to predict vulnerability of these resources to future change.

24

25 **7 Recommendations for management activities to support the continued** 26 **delivery of ecosystem services from soils**

27 Best management practices that support one facet of soil functioning tend to also support
28 others. Building SOM, for example, enhances soil C, soil nutrient status, improves water
29 holding capacity and supports soil biota (Lal, 2004; Smith, 2012). Similarly, preservation of
30 natural ecosystems, and prevention of degradation or conversion to intensive agriculture,
31 almost always benefits soil C, nutrients, water and biota. These synergies, and the
32 fundamental role of soil makes the goal of supporting soil function more straightforward than

1 the goal of maximising multiple ecosystem services, which often involve trade-offs (Robinson
2 et al., 2013; Smith et al., 2013). For example, in terms of the provisioning service of food, the
3 highest per-area yields are often obtained under intensive cropping, with large external inputs
4 of mineral fertilizer, other agro-chemicals (such a pesticides and herbicides) and sometimes
5 water through irrigation (West et al., 2014), with the most intensive forms of agriculture
6 occurring in greenhouses, where external inputs of fertilizers, water and energy can be
7 extremely high (Liu et al., 2008). Though intensive cropping produces high per-area yields, it
8 is not the best management system for a range of other ecosystem services, potentially
9 adversely affecting supporting services (e.g. soil formation through erosion), regulating
10 services (e.g. climate regulation through greenhouse gas emissions; air, water and soil quality
11 through leaching of agrochemicals; pollination through adverse impacts on pollinators) and
12 cultural services (e.g. reduced aesthetic value of the landscape through large scale
13 monoculture; Smith et al., 2013). Balancing the trade-offs between different ecosystems
14 services is, therefore, more difficult than designing management strategies that support soil C,
15 nutrients, water and biota. Tables 1, 2, 4 and 5 present some examples of management
16 activities that affect a range of soil functions, and a number of beneficial management actions
17 occur in most / all of the tables. The most important of these beneficial management activities
18 are described below.

19

20 **7.1 Land cover and use change**

21 A number of meta-analyses (Wei et al., 2014; Guo and Gifford, 2002; Don et al., 2011) show
22 that natural systems lose carbon when converted to agriculture, with the exception of forest to
23 pasture conversion where some studies indicate carbon gain (Guo and Gifford, 2002) while
24 others indicate carbon loss (Don et al., 2011). Given the link between organic matter and soil
25 carbon, nutrients, water and biota, conversion of natural systems to agriculture is likely to
26 adversely impact all of these factors. Protection of natural ecosystems, therefore, benefits soil
27 carbon, nutrients, water and biota. Rewilding of surplus agricultural land would be expected
28 to enhance soil carbon, nutrients, water and biota, as seen in set-aside or reforestation of
29 former cropland (Don et al., 2011). In the absence of land cover / land use change, improved
30 management of agricultural soils can improve soil carbon, nutrient, water and biota (Smith et
31 al., 2015), as described below.

1

2 **7.2 Improved agricultural management**

3 *Reducing soil disturbance* (e.g. through reduced or zero-tillage) is often employed to improve
4 soil moisture retention to enhance soil function, and can also increase SOC stocks (West and
5 Post 2002, Ogle et al., 2005), though the C benefits of no-till may be limited to the top 30cm
6 of soil and some authors argue that the C benefits have been over-stated (Powlson et al.,
7 2014). Baker et al. (2006) found similar soil C in conventional and no-till systems, suggesting
8 that C accumulation is occurring at different depths in the soil profile under different
9 management schemes. Given the tight coupling of soil C and N, increased organic matter also
10 tends to increase nutrient supply, and also enhances water holding capacity (Lal, 2004) which
11 in turn improves the delivery of ecosystem services, and can increase soil biota. Zero tillage
12 also gives rise to greater earthworm and arthropod populations (House and Parmelee, 1985).
13 Perennial crops also reduce the need for annual tillage, and can provide similar benefits.
14 Cultivation of perennial plants with improved rooting systems are likely to increase soil C
15 stocks in C depleted subsoil horizons (Kell, 2012). Land-use change, such as removal of
16 perennial plants and subsequent cultivation, were found to affect both short-lived and long-
17 lived C pools (Beniston et al., 2014).

18 *Maintaining ground cover* through improved residue management, and use of cover crops
19 during traditional bare fallow periods, helps to improve C returns to the soil, prevent erosion
20 and surface sealing, maintain soil nutrients and soil moisture, and supports an active level of
21 soil biota (Lal, 1997). Similar benefits can be achieved through well designed rotations and
22 use of perennial crops or agroforestry (e.g. Mbow et al., 2014).

23 *Use of organic amendments* increases SOM content (Lal, 2004; Smith, 2012; Gattinger et al.,
24 2012), which, as described above benefits soil C, nutrients, water and biota. Organic
25 amendments traditionally include crop residues, animal manures, slurries and composts.
26 These organic matter additions were found to improve C storage and other regulating
27 ecosystem services if repeated regularly. Recent developments, such as the use of biochar or
28 hydrochar from the pyrolysis or hydrothermal carbonization of crop residues or other
29 biomass, can increase SOC stocks and can also reduce soil N₂O emissions and enhance soil
30 fertility (Zhang et al., 2010), which could be effective over multiple years (Liu et al., 2014).
31 However, the properties of these materials and their net effect on ecosystem services, is

1 strongly dependent on production conditions (Wiedner et al., 2013; Naisse et al., 2015). Soil
2 amendment with compost and biochar or their mixture may be particularly useful for
3 increasing the regulating and supporting services of degraded soils (Ngo et al., 2014).
4 Biochar, in conjunction with bioenergy production, is at this stage one of the most promising
5 technologies for achieving the large-scale negative carbon emissions required by mid-century
6 to prevent global mean temperatures from increasing above 2°C, though this is controversial
7 (Fuss et al., 2014).

8 *Optimised timing and rate of fertilizer application:* Intensification has increased annual global
9 flows of N and P to more than double natural levels (Matson et al., 1997, Smil, 2000; Tilman
10 et al., 2002). In China, N inputs to agriculture in the 2000's were twice that in 1980's (State
11 Bureau of Statistics-China, 2005). Optimising the timing and rate of fertilizer applications
12 ensures that the nutrients are available in the soil at a time when the plant is able to take them
13 up, which limits nutrient loss, hence reducing the risk of water pollution and downstream
14 eutrophication (Carpenter et al., 1998). Fertiliser decision support tools can help to implement
15 optimised nutrient management, as can soil testing (to establish soil nutrient status before
16 fertilization), and precision farming, to ensure that nutrient additions are targeted where
17 needed. Subsurface application of slurries to reduce ammonia volatilization can increase
18 nitrous oxide emissions, so there can be trade-offs associated with this practice (Sutton et al.,
19 2007).

20 *Optimised use of agrochemicals:* Reduction in use of broad spectrum bioactive agrochemicals
21 will benefit soil biota. The under-application of pesticides and herbicides could also plausibly
22 have net negative environmental impact, if it means that more land needs to be brought into
23 production (Carlton et al., 2010; 2012). Optimisation of agrochemical applications will also
24 reduce water pollution through leaching.

25 *Water management:* Irrigation of dryland agriculture can increase productivity and C returns
26 to the soil, with the benefits to soil carbon, nutrients, water and biota discussed above, but it
27 can decrease filtration potential and increase the risk of soil salinization (Ghassemi et al.
28 1995; Setia et al., 2011). In waterlogged marginal lands, drainage can increase productivity
29 and thereby increase carbon returns to the soil, while decreasing methane and nitrous oxide
30 emissions. If wetland soils are drained, oxidation of organic soils will lead to large losses of
31 soil C and the nutrients associated with it; and decrease the ability of these soils to carry
32 out services like water purification (e.g. through denitrification). Drainage of peatlands has

1 been associated with increased runoff and flood risk (Ballard et al., 2012). In terms of
2 biodiversity, productivity of drained marginal lands can increase at the expense of plant
3 genetic diversity.

4 *Improved grazing management* (e.g. optimised stocking density) can reduce soil degradation,
5 and thereby maintain and enhance organic matter content (McSherry and Ritchie, 2013)
6 benefiting soil C, nutrients, water and biota as described above. Higher productivity and deep
7 rooted grasses can do similarly (Kell, 2012), while also modifying water use efficiency, but
8 potentially at the expense of plant genetic diversity. Reduction in grazing density can reduce
9 soil compaction, and therefore increase infiltration and water storage and reduce risk of runoff
10 and flooding downstream (Marshall et al., 2009). Fire management can also increase soil C
11 and nutrient status of soils (e.g. Certini, 2005).

12

13 **8 Conclusions**

14 Many practices are known to enhance all or most of the functions of soils considered in this
15 review which is encouraging for our efforts to protect soils into the future. Soils are complex,
16 there are still knowledge gaps (outlined in section 6), and fundamental research is still needed
17 to better understand the relationships between different facets of soils and the array of
18 ecosystem services they underpin. There is a tendency to dwell on the complexity and
19 knowledge gaps, rather than to focus on what we do know, and how this knowledge can be
20 put to use to improve the delivery of ecosystem services. While more knowledge is required
21 on where specific agricultural systems are best placed to utilise and deliver ecosystem
22 services most efficiency, to protect and enhance our soils in the long-term, best practices are
23 well characterised and many can be implemented immediately. Despite a growing population
24 and increasing demands for resources, enough is known to discriminate the extremes of
25 beneficial and detrimental agricultural practices, and their interactions with different types of
26 soils. A significant challenge is to find effective ways to share this knowledge with soil
27 managers and policy makers, so that best management can be implemented. A key element of
28 this knowledge exchange must be in raising awareness of the ecosystems services
29 underpinned by soils, and thus the natural capital they provide (Robinson et al., 2013). We
30 know enough to start moving in the right direction, while we conduct research to fill in our
31 knowledge gaps. So a challenge to soil scientists is to better communicate what we do know,
32 while we carry out research to better understand the things that we do not know. The lasting

1 legacy of the International Year of Soils in 2015 should be for soil scientists to work together
2 with policy makers and land managers, to put soils at the centre of environmental policy
3 making and land management decisions.

4

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13

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1 Table 1. Management actions affecting the soil carbon cycle and their impact on ecosystem services.

Management action or other driver of change	Provisioning service impact	Regulating service impact	Supporting service impact	Cultural service impact
Land-use change (conversion of forest/grassland/wetland to cropland)	Increased production of food, fibre, and energy crops; reduced availability of natural raw materials; potential change in hydrology/water availability	Decreased soil C sequestration and storage - increased GHG flux; increased erosion and sediment yield – reduced regulations of water flow and quality;	Primary production may be changed; nutrient recycling reduced if no inputs, increased if there are inputs;	Lower recreation value; may have impact on cultural value in recreating diverse landscapes
Land-use-change (establishment of forest or grassland on agricultural land)	Raw material provision may be increased; agricultural production likely decreased (but not always e.g. agroforestry)	Increased C sequestration; increased regulation of water flow and quality	Primary production may be changed, increased water recycling	Increased recreation value; may have impact on cultural value in recreating diverse landscapes
Intensified nutrient management through fertilisation and liming	Increased production of food and other raw materials	Effect on net soil C sequestration uncertain; increased GHG flux from fertiliser production and use; water and air pollution	Increased primary production; increased nutrient recycling	
Soil amelioration using organic amendments such as compost and biochar	Increased food production; more raw materials; more water available for plant growth	Increased C sequestration; increased water purification value	Increased primary production; increased nutrient cycling; improved water infiltration and retention	
Diversification of crop production systems (i.e., more perennials, reduced bare fallow)	Potential impact on agricultural production (+/-); more diverse products	Increased C sequestration; increased purification value	Changed primary production; increased nutrient retention; improved water infiltration and retention	Improved cultural value from more diverse landscapes
Replacement of hay forage production with pasture use on grasslands	No impact	Effect on C sequestration uncertain		Increased recreation value; may have impact on cultural value in recreating diverse landscapes
Improved grazing management	Increased food production; reduced runoff and improved water use	Increased C sequestration; increased purification value; water flow regulation	Increased primary production; improved water infiltration and retention	

2

1 Table 2. Management actions affecting soil nutrient cycles and their impact on ecosystem services.

Management action or other driver of change	Provisioning service impact	Regulating service impact	Supporting service impact	Cultural service impact
Intensive addition of mineral fertilizers	Increased food, fibre and feedstock production;	Reduced water quality through eutrofication, reduced air quality through emission and volatilization of reactive N gases	Increased primary production. Alteration of the nutrient and C cycling. Possible reduction of biodiversity	
Use of organic soil amendments (e.g. manure, composts and biochar)	Increased food, fibre and feedstock production; may increase water retention	Increase C sequestration	Increase nutrient retention	
Implementation of No- tillage			increase nutrient retention	
Precision agriculture	Increase efficient production of food	Reduced GHG emissions per unit production	Reduce consumption of water and nutrient, by improving use efficiency	
Prescribed use of fire for pasture management	Increase feedstock production	Increase C sequestration, by conversion to BC	Reduce N recycling, by storing black nitrogen	
Use of biological soil supplements	Stimulate productivity; act as fertilizers	May improve pest and disease control	Improved nutrient cycling	

2

1 **Table 3.** Soil functions related to the water cycle and ecosystem services.

Soil Function	Mechanism	Consequence	Ecosystem service
Stores (Storage)	Water held in soil pores supports plant and microbial communities	Biomass production Surface protection	Food Aesthetics Erosion control
Accepts (Sorptivity)	Incident water infiltrates into soil with excess lost as runoff	Storm runoff reduction	Erosion control Flood protection
Transmits (Hydraulic conductivity)	Water entering the soil is redistributed and excess is lost as deep percolation	Percolation to groundwater	Groundwater recharge Stream flow maintenance
Cleans (Filtering)	Water passing through the soil matrix interacts with soil particles and biota	Contaminants removed by biological degradation/ retention on sorption sites	Water quality

2

1 **Table 4.** Management actions affecting the soil water cycle and their impact on ecosystem services.

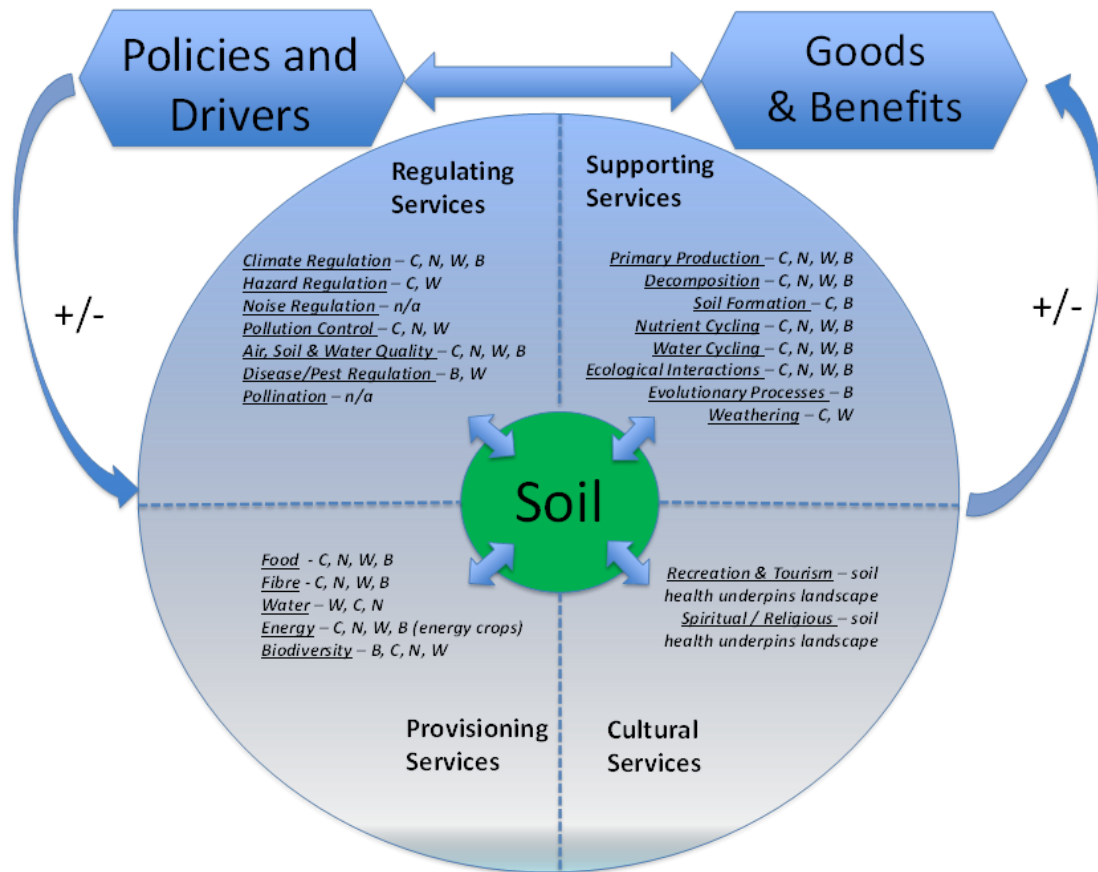
Management action or other driver of change	Provisioning service impact	Regulating service impact	Supporting service impact	Cultural service impact
Land use change (increase change of agricultural to urban)	Decreased biomass, decreased availability of water for agricultural use.	Increased impervious surface, decreased infiltration, storage, soil mediated water regulation	Decreased genetic diversity; reduction of rainfall recycling e.g. in the tropics	Decreased natural environment
Land use change (increase change of arable to intensive grassland)	Increased yield of animal over vegetable protein.	Increased C sequestration, greater requirement of water, stress on ecosystem health of downstream waterways	Increased genetic diversity associate with mixed pastures	Change from traditional values and aesthetic value
Irrigation (increase)	Increased biomass over dryland agriculture, decreased availability of water for urban use	Increased C sequestration, but decreased filtration potential	Improved habitat for plant species	Infrastructure alters landscape decreasing spiritual connection with catchment
Drainage (increasing in marginal land)	Decreased soil saturation, increased biomass, removal of wetlands	Decreased C sequestration, denitrification and flood attenuation	Better habitat for productive grassland plants, but loss of genetic diversity	Decreased recreational potential (e.g. ecotourism)

2

1 **Table 5.** Management actions affecting the soil biota and their impacts on ecosystem services.

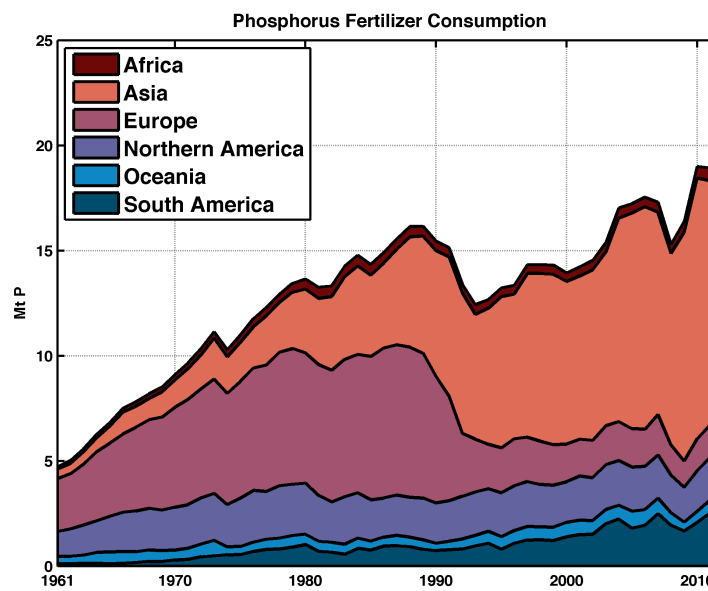
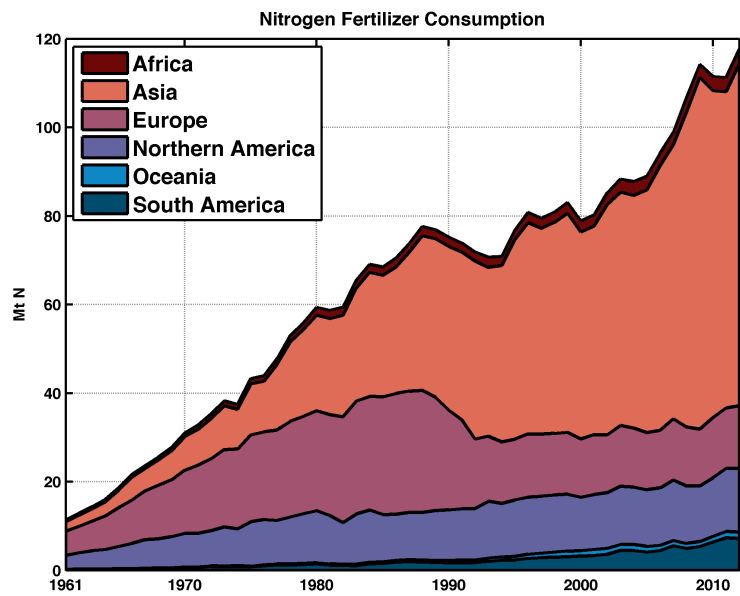
Management action or other driver of change	Provisioning service impact	Regulating service impact	Supporting service impact	Cultural service impact
Land use change of natural vegetation to agricultural intensification	Changed genetic resources, changed production of (precursors to) industrial and pharmaceutical products	Decreased C sequestration, changed pest and disease control	Changed elemental transformation	Changed diversity of soil organisms (elimination of some soil animals, etc.)
Use of organic amendments	Increased genetic resources, decreased production of (precursors to) industrial and pharmaceutical products	Increased C sequestration	Increased soil formation, increased primary production by phototrophs, changed elemental transformation	Increase of soil organisms
Use of broad spectrum bioactive agrochemicals	Decreased genetic resources, decreased production of (precursors to) industrial and pharmaceutical products	Possible decreased waste decomposition and detoxification	Decreased primary production by phototrophs, changed elemental transformation	Decreased diversity of soil organisms (elimination of some soil animals, etc.)
Pollution by heavy metals or xenobiotics	Decreased genetic resources, decreased production of (precursors to) industrial and pharmaceutical products	Possible decreased waste decomposition and detoxification	Decreased primary production by phototrophs, changed elemental transformation	Decreased diversity of soil organisms (elimination of some soil animals, etc.)
Climate change (global warming)		Possible decreased C sequestration	Changed elemental transformation	

2



1

2 Figure 1. Schematic representation of where soil carbon, nutrient and water cycles, and soil biota underpin ecosystem services (adapted from
 3 Smith et al., 2014). Role in underpinning each ecosystem service shown by C = soil carbon, N = soil nutrients, W = soil water, B = soil biota.
 4 Only soil carbon, nutrient and water cycles, and soil biota are considered, so the Figure does not represent a comprehensive overview of soil
 5 ecosystem services, which have been reviewed recently elsewhere (e.g. Robinson, et al., 2013; 2014).

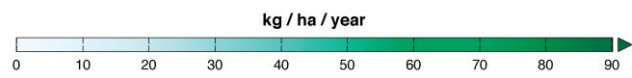
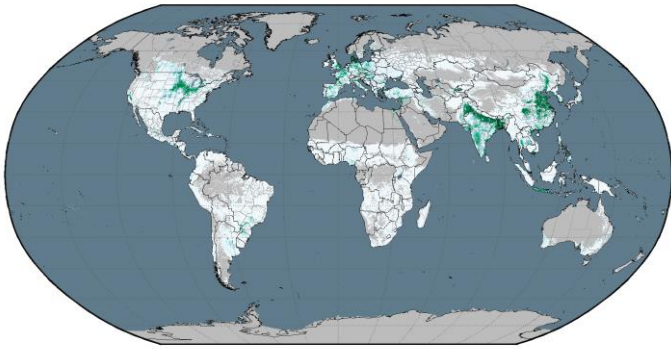


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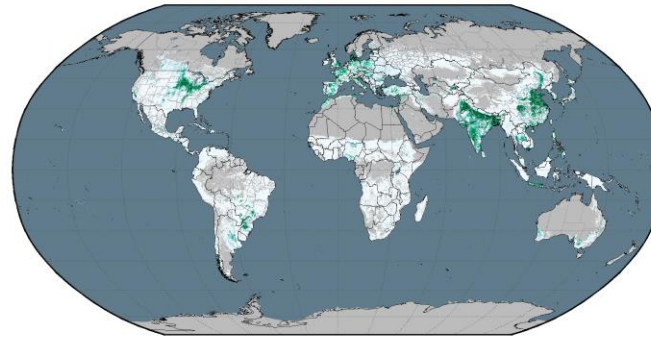
2 Figure 2. Global (a) nitrogen (N) and (b) phosphorus (P) fertilizer use between 1961 and 2012 split for the different continents in Mt P per
 3 year; plotted from FAOSTAT data (FAOSTAT, 2015).

4

Applied Nitrogen

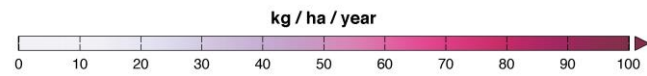
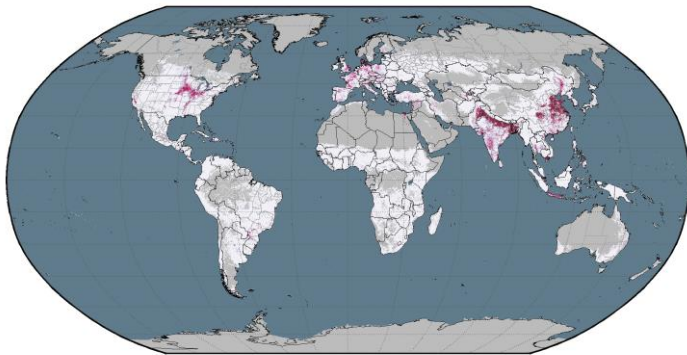


Applied Phosphorus

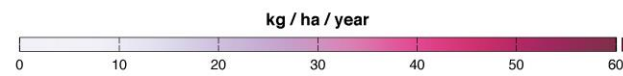
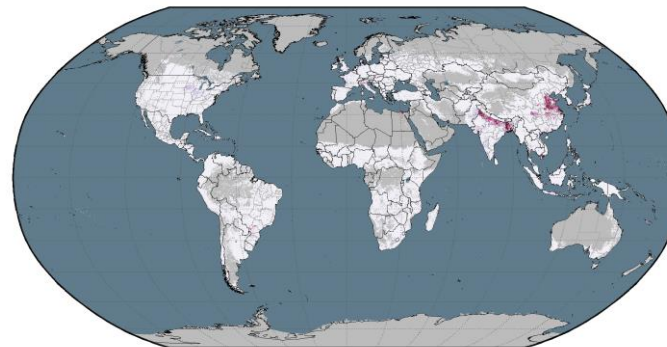


1

Excess Nitrogen



Excess Phosphorus



2

1 Figure 3. Applied and excess nitrogen and phosphorus in croplands. Nitrogen and phosphorus inputs and excess were calculated using a
2 simple mass balance model (West et al., 2014), extend to include 175 crops. To account for both the rate and spatial extent of croplands, the
3 data are presented as kg per ha of the landscape. Fig 3a Applied Nitrogen, including N deposition; Fig 3b Applied Phosphorus; Fig 3c;
4 Excess Nitrogen Fig 3d; Excess Phosphorus.