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Soil management in relation to sustainable agriculture and ecosystem services ☆

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ABSTRACT

Requirements for research, practices and policies affecting soil management in relation to global food security are reviewed. Managing soil organic carbon (C) is central because soil organic matter influences numerous soil properties relevant to ecosystem functioning and crop growth. Even small changes in total C content can have disproportionately large impacts on key soil physical properties. Practices to encourage maintenance of soil C are important for ensuring sustainability of all soil functions. Soil is a major store of C within the biosphere – increases or decreases in this large stock can either mitigate or worsen climate change. Deforestation, conversion of grasslands to arable cropping and drainage of wetlands all cause emission of C; policies and international action to minimise these changes are urgently required. Sequestration of C in soil can contribute to climate change mitigation but the real impact of different options is often misunderstood. Some changes in management that are beneficial for soil C, increase emissions of nitrous oxide (a powerful greenhouse gas) thus cancelling the benefit. Research on soil physical processes and their interactions with roots can lead to improved and novel practices to improve crop access to water and nutrients. Increased understanding of root function has implications for selection and breeding of crops to maximise capture of water and nutrients. Roots are also a means of delivering natural plant-produced chemicals into soil with potentially beneficial impacts. These include biocontrol of soil-borne pests and diseases and inhibition of the nitrification process in soil (conversion of ammonium to nitrate) with possible benefits for improved nitrogen use efficiency and decreased nitrous oxide emission. The application of molecular methods to studies of soil organisms, and their interactions with roots, is providing new understanding of soil ecology and the basis for novel practical applications. Policy makers and those concerned with development of management approaches need to keep a watching brief on emerging possibilities from this fast-moving area of science. Nutrient management is a key challenge for global food production: there is an urgent need to increase nutrient availability to crops grown by smallholder farmers in developing countries. Many changes in practices including inter-cropping, inclusion of nitrogen-fixing crops, agroforestry and improved recycling have been clearly demonstrated to be beneficial: facilitating policies and practical strategies are needed to make these widely available, taking account of local economic and social conditions. In the longer term fertilizers will be essential for food security: policies and actions are needed to make these available and affordable to small farmers. In developed regions, and those developing rapidly such as China, strategies and policies to manage more precisely the necessarily large flows of nutrients in ways that minimise environmental damage are essential. A specific issue is to minimise emissions of nitrous oxide whilst ensuring sufficient nitrogen is available for adequate food production. Application of known strategies (through either regulation or education), technological developments, and continued research to improve understanding of basic processes will all play a part. Decreasing soil erosion is essential, both to maintain the soil resource and to minimise downstream damage such as sedimentation of rivers with adverse impacts on fisheries. Practical strategies are well known but often have financial implications for farmers. Examples of systems for paying one group of land users for ecosystem services affecting others exist in several parts of the world and serve as a model.

Introduction

"The nation that destroys its soil, destroys itself".
–Franklin D. Roosevelt.

☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

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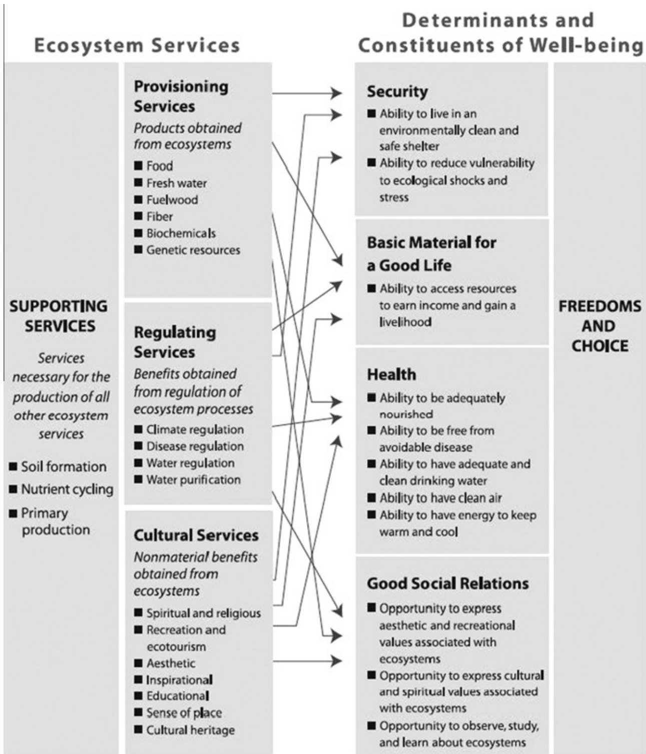

Fig. 1. Ecosystem services and their links to human well-being, as described in the conceptual framework of the Millennium Ecosystem Assessment.

"While the farmer holds the title to the land, actually it belongs to all people because civilisation itself rests upon the soil".
–Thomas Jefferson.

These two US Presidents recognised the importance of soil, not only for food production, but for the future of mankind. This should come as no surprise as soil functioning is fundamental or contributory to virtually all of the "provisioning", "regulating" and "cultural" services identified in the Millennium Ecosystem Assessment – see Fig. 1 (http://www.millenniumassessment.org/en/Framework.aspx).

Soil functions required by humanity are elaborated in the EU Soil Thematic Strategy (http://ec.europa.eu/environment/soil/three_en.htm). Rather than repeat these, we list below some specific soil functions essential for food production:

1. An environment for seed germination, root growth, and the functioning of roots to provide anchorage and absorb water and nutrients.
2. Provision of reserves of nutrients within organic matter and mineral components, which are released into plant-available forms at different rates.
3. The pathway through which water and nutrients move to roots, whether from soil reserves or from external inputs.
4. The matrix in which transformations of nutrients occur through biological, chemical and physical processes, with major implications for crop uptake and losses.
5. An environment for microorganisms and fauna, which may be beneficial, harmful or neutral towards crop plants. Many organisms are central to the transformations of organic matter, nutrients and pollutants with major implications for agricultural production and ecosystem processes.
6. A platform for machinery, humans or animals involved in agricultural operations.

Some functions of wider societal or ecosystem significance include:

1. Not moving: i.e. not being subject to erosion, mudslides or landslips and thus providing a stable surface for a range of human or natural activities.
2. Absorbing water and thus retaining it for use by vegetation and transfer to rivers and streams. The opposite is surface runoff in which water moves rapidly to rivers, and ultimately to oceans, with little replenishment of soil water storage and increased risk of soil erosion and transfer of sediment to surface waters.
3. Influencing water quality, positively or negatively, by regulating the transformations and movement of nutrients, pollutants and sediments to surface- or ground-waters.
4. Influencing the composition of the atmosphere particularly through acting as source or sink for several greenhouse gases.
5. Providing a habitat for soil biota which represent a vast source of biodiversity.
6. Providing a basis for natural or semi-natural vegetation which, in turn, provides habitat and resources for the animal kingdom.

Utilising soil for agriculture inevitably leads to changes in soil properties such as nutrient status, pH, organic matter content and physical characteristics. In many cases changes that are beneficial for food production are detrimental for other ecosystem services, so there is a tension between the different functions of soils.

Table 1
From Vitousek et al. (2009).

Agricultural region »	Nutrient balances (kg ha^{-1} yr^{-1})					
	Western Kenya		North China		Midwest USA	
	N	P	N	P	N	P
Fertilizer	7	8	588	92	93	14
Biological N fixation					62	
Total agronomic inputs	7	8	588	92	155	14
Removal in grain and/or beans	23	4	361	39	145	23
Removal in other harvested products	36	3				
Total agronomic outputs	59	7	361	39	145	23
Agronomic inputs minus harvest removals	−52	+1	+227	+53	+10	−9

Inputs and outputs of nitrogen and phosphorus in harvested products in a low-input corn-based system in Western Kenya in 2004–2005 (8), a highly fertilized wheat–corn double-cropping system in North China (2003–2005) (9–11), and a tile-drained corn-soybean rotation in Illinois, USA (1997–2006) (14). Potential crop yields are similar in these systems, but realized yields of corn were 2000, 8500, and 3200 kg ha^{-1} yr^{-1} per crop in the Kenya, China, and US systems, respectively. Wheat yielded another 5750 kg ha^{-1} yr^{-1} in China, and soybeans yielded 2700 kg ha^{-1} yr^{-1} every other year in Illinois. (Because the Illinois system represents a 2-year rotation, all nutrient inputs and removals were adjusted to place them on an annual basis.)

Quite understandably, in many parts of the world maximising food production at all costs is still the over-riding motivation due to poverty and the resulting lack of food security; wider environmental impacts and longer-term consequences are easily overlooked, even though, in academic circles, the inter-relationships between food production and other ecosystem services are now recognised. Even on the timescale of several human generations, soils are non-renewable. So a priority for soils research is to provide the basis for management practices that avoid irreversible damage to the soil resource, leading to agricultural systems that are sustainable in the sense enunciated in the Bruntland Report "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Report of the World Commission on Environment and Development: Our Common Future; http://www.un-documents.net/wced-ocf.htm).

The aim of this review is to highlight some key issues for soil functioning that require research if food production is to increase sufficiently to meet the needs of the 9 billion people expected by 2050 (Royal Society, 2009). In some cases we point out that the priority is to implement policies to promote the application of current knowledge; in other cases new research is required to provide enhanced understanding as the basis for improved management. Where appropriate we make separate comments on differing priorities in developed and developing regions of the world. Suggestions for policy or action appropriate for different topics are summarised in the final section and in Table 2.

Managing organic carbon in soil

Soil carbon – quantity, structure and soil functions

After texture, acidity and salinity, organic carbon content is the variable having the greatest impact on soil properties. Long-term experiments show that the content of soil organic carbon (SOC) is the result of a balance between the inputs and outputs of organic C (e.g. Johnston et al., 2009; Lützow et al., 2006).The main C inputs are plant roots and root exudates, above-ground plant residues and manures or other organic by-products. Outputs are the decomposition of organic matter by soil microorganisms and fauna leading to evolution of CO_2 to the atmosphere (or CH_4 under anaerobic conditions), leaching of soluble organic C compounds and particulate losses through erosion. Decomposition is normally the dominant output process and is controlled by clay content, temperature, moisture content and oxygen availability within the soil. Soils with a higher content of clay-sized particles, or higher cation exchange capacity, normally move towards a higher equilibrium content of organic C than sandy soil due to their greater capacity for stabilising microbial metabolites. The total SOC content of a soil under specified management practices can often be predicted with some success using several current models (Smith et al., 1997) though further research is required for some situations including peat soils, simulating impacts of reduced tillage and the dynamics of fractions within the total.

Much research has been devoted to elucidating the chemical structure of SOM and in recent years this has been aided by the use of a range of spectroscopic techniques (e.g., Mahieu et al., 1999; Spaccini et al., 2009). From the viewpoint of providing information as a basis for management practices, it is important that such research is strongly linked to soil functions, rather than seen as purely academic study. It is thought that the metabolites from microbial action are further modified by both exo-cellular enzymes and physico-chemical processes, including reactions influenced by the surface chemistry of soil inorganic particles, and probably free radicals. Thus, the resulting organic matter is not formed under purely genetic control, unlike microbial or plant metabolites, so is likely to incorporate a degree of randomness in its structure rather than being true polymers composed of regular repeating units. Whilst specific chemical structures are useful as models in understanding processes, they almost certainly do not exist in a pure form in nature.

Soils converted from natural vegetation to arable cropping decline in SOC content until a new equilibrium level is reached. From almost any viewpoint, it is desirable to maintain SOC content at as high a value as possible for the soil type and environment as this is beneficial for a wide range of soil physical properties and root growth. Loveland and Webb (2003) reviewed the literature on whether "critical levels" of SOC can be defined. They concluded that there was little quantitative evidence for critical thresholds for soils in the temperate regions but drew attention to evidence that certain small fractions of SOC within the total (termed "fresh" or "active" organic matter) were especially important in determining physical properties such as aggregation which are highly relevant to food production and soil responses to human impacts. This is consistent with observations that small changes in total C content can have disproportionately large effects on a range of soil physical properties including aggregate stability, water infiltration and energy required for tillage (Blair et al., 2006; Watts et al., 2006). Without massive supplies of organic materials such as manure it is extremely difficult to substantially increase SOC content of arable soils. Consequently, developing an understanding of mechanisms to maximise the benefits of small inputs is of high priority.

Changes in the organic C content of soil often occur slowly, so long term experimental sites are an invaluable resource for studies of the impacts of management and land use; see Richter et al (2007) for a discussion.

Soil carbon and the global carbon cycle

The world's soils contain a large stock of C, estimated at 2157–2293 Pg to a depth of 1 m, comprising 1462–1545 Pg in organic forms and 695–748 Pg as carbonate (Batjes, 1996). Organic C in the surface 30 cm, which is most liable to change as a result of management or climate change, is estimated at 684–724 Pg: about twice the quantity of C currently in CO_2 in the atmosphere. This large stock of soil C represents both a *threat* and an *opportunity* in the context of the global C cycle and climate change. A serious current *threat* is the release of soil organic C as CO_2 to the atmosphere, mainly due to deforestation and the drainage of peat. A particularly perverse example of land use change is clearance of vegetation on high-C soils in order to grow biofuels as a means of climate change mitigation. It is estimated to take up to 100 years to recoup the C lost from soil in the energy gained from biofuel (and thus fossil fuel saved).

The *opportunity* is to manage soils in such ways as to sequester additional C from the atmosphere. This can be achieved by planting new forests (or other perennial semi-natural vegetation) on land with a low SOC content (due to past degradation or long-term arable cropping; e.g. Poulton et al., 2003). In principle the quantities of C that could potentially be sequestered in these ways are large on a global basis (Smith et al., 2008), but there are significant practical limitations which are sometimes overlooked. In view of the need for increased food production there are clearly limits to the area of land that can be taken out of production and the issue of indirect land use change (Searchinger et al., 2008) must be considered: i.e. food production lost through taking land taken out of production at one location being made up by forest clearing elsewhere, with the concomitant release of C cancelling out the C benefit at the other location. For soils continuing in agricultural production, some opportunities for additional C storage do exist but are limited and sometimes misunderstood. For an increase in SOC to mitigate climate change there must be a net transfer of C from atmosphere to soil; this may either be through: (1) additional photosynthesis and transfer of photosynthate to soil, or (2) through slower decomposition of organic matter in soil. A common misunderstanding is that *any* SOC increase achieved through a change in management practice can be regarded as climate change mitigation. This is not the case as some changes in land management (e.g., manure application) are simply a transfer of organic C from one location to another (see Powlson et al., 2010). Many practices likely to genuinely sequester additional C in agricultural soils would require major changes in cropping systems or significant research. Possible approaches include intercropping with perennials, agroforestry systems, selection or breeding of crops with larger or deeper roots.

Because subsoils generally contain a lower concentration of organic C than topsoil there is, in principle, greater potential for increased storage. There is also some evidence that organic C in subsoil is stabilised to a greater degree than that in topsoil (Jenkinson and Coleman, 2008), though the mechanisms involved are still poorly understood and debated (Fontaine et al., 2007; Salomé et al., 2010). Plant roots provide an obvious means of delivering organic C into subsoil; it may be possible to exploit different rooting depths or exudation characteristics between arable crop cultivars to achieve this. Carter and Gregorich (2010) investigated this for perennial grasses. For a critical review of such possibilities see: http://sciencesearch.defra.gov.uk/Document.aspx?Document=SP1605_9703_FRP.pdf.

Minimum or zero tillage are often claimed to deliver C sequestration through decreased SOC decomposition. However recent re-evaluation of data (Baker et al., 2007; Angers and Eriksen-Hamel, 2008) indicates that the net accumulation of C under reduced tillage, whilst measurable in the long term, is much less than previously claimed. Much of the effect is a concentrating of SOC nearer the soil surface than in tilled soil. In many soil types and environments, though not all, this can have numerous beneficial effects including improved soil structure near the surface which is beneficial for seedling emergence increased water infiltration. Reduced soil disturbance can also lead to decreased evaporation – of great importance in areas of low rainfall. Thus reduced tillage can often deliver a range of benefits for crop production; its rapid expansion in many areas such as South America has generally been led by farmer initiatives rather than research. It often forms part of a system termed "Conservation agriculture" (CA) which combines minimum soil disturbance, permanent soil cover by plants, beneficial crop rotations and return of residues such as straw – see http://www.fao.org/ag/ca.

A negative impact of zero tillage is that, in moist environments, it can lead to increased emission of nitrous oxide (N_2O; Rochette, 2008; Baggs et al., 2003; Ball et al., 2008). Thus, in relation to climate change mitigation, the small SOC benefit from C sequestration under reduced tillage could easily be outweighed by increased N_2O emissions. But in view of the many practical benefits of the system, research is needed to investigate whether this disadvantage can be overcome.

Emerging topics for research or action

1. Assessments of realistic quantities (rather than potential) for soil C sequestration as a climate change mitigation option in a variety of environments and land uses worldwide.
2. Policy responses to the current losses of soil C from land clearance, especially where this is justified by use of cleared land for biofuel production.
3. Research to better define interactions between components of soil organic matter and inorganic materials in soil, including nutrient and pollutant ions or molecules, as a basis for better informed management of nutrient and pollutant availability or immobilisation.
4. Identifying specific fractions of soil organic matter as substrate for different groups of microorganisms in order to better understand the factors influencing the ecology of microbial populations and, potentially, influencing populations for the benefit of crop production.
5. Defining the mechanisms by which specific components of SOC influence soil physical properties through altering interactions between mineral particles that influence aggregate formation and stability, and pore size distribution. This knowledge will underpin development of management practices to improve soil functioning whilst using only limited and realistic supplies of organic matter.
6. The possibility of reducing CO_2 emissions from agricultural soils by replacing agricultural lime with waste silicates (Renforth et al., 2009).

Optimising soil physical conditions for crop growth in a range of environments

A soil physical environment conducive to root growth is a basic requirement for productive agriculture. Extreme weather conditions, predicted to become more prevalent under climate change, both wetter and drier, cause stresses that exacerbate any underlying soil physical problems.

Water availability to crops and the phenomenon of "strong soils"

In drought environments it is usually assumed that the key soil stress limiting crop growth is water availability. However, as soil dries there is evidence to show that increased soil strength can significantly reduce root and shoot elongation in relatively well-watered situations, not associated with droughts (Whalley et al., 2006; Whitmore and Whalley, 2009). This phenomenon is commonly overlooked as a yield limiting problem, although it has long been recognised (Masle and Passioura, 1987). Solutions require research involving interactions between plant genetics and physiology and soil properties during drying. Much research on the effects of water stress on plant growth has used model systems where water potentials are adjusted independently of all other stresses (e.g. Verslues et al., 1998); thus the influence of soil strength on crop access to water, and its interactions with other stresses, is overlooked. To make progress of practical value to crops under realistic field conditions, it is essential that soil and plant factors, and their interactions, are integrated in future research (Mittler, 2006).

A key issue is understanding how root length distribution and root architecture interact with soil profile properties to confer drought tolerance (Manschadi et al., 2006, 2008). While it is often assumed that simple access to water at depth limits yield in drought, Blum et al. (1991) concluded that surface drying rather than a lack of access to water at depth was responsible for yield loss in wheat. The effect of surface drying in limiting yield is attributed to signals from the root that determine the growth of the crop canopy (Dodd, 2005). Recently it has been demonstrated that different parts of the root system can contribute to specific signals present in the xylem according to the relative degree of stress and hydration in different regions of the root system (Dodd et al., 2008). Research to provide mechanistic understanding of such signalling is an essential building block for designing soil and crop management practices that optimise efficiency of use of water and nutrients, thus decreasing the carbon footprint of agriculture.

Organic matter and soil physical properties

Although empirical evidence shows that bulk density decreases with increasing organic matter content (Whalley et al., 2007), mechanistic understanding of organic matter influences on soil physical conditions is lacking. The water release characteristic (or the saturation at a given matric potential) and bulk density are key factors that determine the mechanical impedance to root growth. (Matric potential is a measure of the suction due to capillary action within soil pores.) The relationships between soil water content, matric potential, and mechanical impedance are non-linear. This is consistent with the observation that small differences in organic carbon content can have a disproportionally large effect. In essence, properties at the microscopic scale are likely to have a large impact on the field scale behaviour of soil. However, the microscopic behaviour and structure of soil is poorly understood: basic research is required to provide understanding for developing improved management practices.

Managing nutrients in diverse environments and cropping systems

Together with water, managing the supply of nutrients to crops is probably the greatest challenge in securing world food supply without causing unacceptable environmental impacts. The vast range of conditions worldwide with respect to nutrient supply has been characterised as ranging "from feast to famine" (Brookes et al., 2010), indicating chronic deficiency in some regions and vast over-supply in others. This is summarised in Table 1 showing nitrogen (N) and phosphorous (P) budgets for maize-based cropping systems in three regions of the world. In western Kenya removal of N in crops exceeds inputs – clearly an unsustainable situation leading to depletion of nutrients in soil and inevitably declining yields. Outputs of P are small because maize yield is constrained to only 2 t ha^{-1} due to N deficiency compared to >8 t ha^{-1} in the two other regions. The North China Plain shows the opposite: inputs of N and P from fertilizer and manure greatly exceed removals in crop and lead to wastage of resource and cause environmental pollution as they escape from soil to the wider environment.

Situations of nutrient shortage

In regions such as Africa where shortage of nutrients is a major constraint to food production the following are key issues:

1. Policy and economic approaches to increase access to fertilizers for resource-poor farmers (Sanchez, 2002). Improving transport infrastructure or establishing local manufacture is obviously a long-term undertaking, but in the short term, packaging of fertilizer in small quantities suitable for smallholder farmers, probably at a subsidised price, is a policy with great potential for an immediate impact – especially if combined with other agronomic packages (new crop varieties, technical advice) and development of marketing opportunities. This is part of the strategy of the Alliance for a Green Revolution in Africa, AGRA; see http://www.agra-alliance.org/section/about. Harrigan (2008) reviewed the benefits and limitations of a "starter pack" scheme used in Malawi comprising free handouts of packs containing improved maize seed, legumes and fertilizer. This author concluded that, whilst the scheme was not a panacea for eliminating poverty, it provided a platform on which to build rural growth strategies.
2. Technical approaches to making small quantities of fertilizer make a large impact. Examples include placement of fertilizer granules close to individual plants, which is entirely practical for widely spaced crops such as maize grown on small areas, and small "starter" doses of fertilizer to increase early growth of roots giving the plant access to a larger volume of soil (e.g. Ncube et al., 2007).
3. Innovative agronomic managements to better utilise nutrients from sources other than fertilizers including soil reserves, recycling from crop residues, manures or household wastes, and biological nitrogen fixation, and management of intercropping or agro-forestry to maximise different rooting patterns (e.g. Sanchez et al., 2007). Although the principles underlying such approaches are generic and often simple, their application requires much region-specific research and participation of farmers. Even when such innovations are introduced, the introduction of fertilizers is still vital as shown in the Millennium Villages project (Sanchez et al., 2007). This is emphasised by estimates of global food production assuming that N from biological fixation by legumes were the only N input. Using plausible but optimistic assumptions, Connor (2008) estimated that such systems could feed 4.2 billion people at best. A more realistic assumption is that 50% of the land would need to grow a legume as part of a rotation thus reducing productivity to one crop in two; this might feed 3.1 billion. With world population at 6.7 billion and likely to reach about 9 billion by 2050, it is clearly impossible for legumes to meet even the current N requirement for food security. Worse, Jones and Crane (2009) found that yields of wheat from a legume-based system in the UK would be one third of that from wheat grown using nitrogen fertilizer. This is because the need for a fertility-building phase in the rotation eliminates some years of production. Thus the GHG emission per tonne of grain is three time greater in a legume-based system than one relying on fertilizer N, at least under UK conditions, and almost outweighs the emissions from manufacture and use of N. This assumes that there are no N_2O emissions from legume-derived N; almost certainly not the case (Jensen et al., 2010).

Situations with adequate or excess nutrients

In these regions it is helpful to distinguish between mature intensive agricultural systems that have developed over many years with farmers now having a high level of education (broadly Europe, North America, Australasia) and regions of current rapid development (China and parts of India, southeast Asia and South America). For example, in China there is overwhelming evidence of over-use of fertilizers (Table 1), especially N, with major environmental impacts such as eutrophication of surface waters, exceeding limits for nitrate in drinking water and the acidification of soils (Guo et al., 2010). In part this is due to (understandable) government policies to increase food production, virtually at all costs, combined with a lack of understanding by relatively poorly educated farmers. The situation can be regarded as an "over-shoot" with fertilizer use increasing from almost zero to the highest in the world over a period of about 40 years.

In regions favourable to grain production annual yields in excess of 10 t grain ha^{-1} (wheat, maize or rice in either single or multiple cropping) are commonly attained. If future food security is to be achieved such yields will need to be sustained and increased through a combination of improved crop varieties and agronomic management. Such yields inevitably require large inputs of nutrients. For example, winter wheat crops in north-west Europe yielding about 10 t grain ha^{-1} typically remove about 200 kg N ha^{-1} annually: this N needs to be supplied from a variety of sources of which fertilizers necessarily form a large part. With the large inputs of N required for high yield the risk of loss increases, representing an economic and resource waste and also causing environmental damage. Fig. 2 illustrates this for winter wheat in the long-term Broadbalk Experiment at Rothamsted, UK. When the rate of fertilizer N applied exceeds that required to achieve maximum yield, unused nitrate remains in the soil and is at risk of leaching in the following winter. Similar relationships exist for other mechanisms of N loss. There is continued need for research on N cycle processes so that management strategies can be designed or further refined that minimise the risk of N loss in highly productive systems that necessarily require high N inputs. Some key issues include the following:

1. Decreasing emissions of nitrous oxide (N_2O) from soils, from N supplied as fertilizer, organic manures or from biological N fixation: N_2O is a very powerful greenhouse gas, with 296 times greater global warming potential than CO_2. Although N_2O losses (from both nitrification and denitrification) are often relatively small in agronomic terms, even small losses represent a significant contribution to the overall greenhouse gas footprint of agriculture. The IPCC default value for direct loss is 1% of applied N, though this is greatly influenced by environmental and management factors. Research to better define these controlling factors for a range of environments and cropping systems is a major priority. Nitrification inhibitors appear to offer a promising approach (Richardson et al., 2009; Di and Cameron, 2006; Watson et al., 2009), but are not universally successful (Saggar et al., 2008).
2. In addition to direct emissions of N_2O at the point of N application, indirect losses are recognised as being significant and possibly even greater (Crutzen et al., 2008). These can arise from (a) denitrification of nitrate leached from soil to waters such as rivers, lakes and estuaries, (b) ammonia volatilised from the soil surface subject to nitrification, and potentially denitrification, after redeposition.
3. Decreasing ammonia volatilisation from urea fertilizer and from animal manures through improved understanding of the controlling factors and design of application techniques to decease losses. In addition to representing a serious agronomic and economic waste, ammonia deposited on soil or water causes acidification (Goulding et al., 1998) and contributes to indirect N_2O emissions.

In addition to research on the transformations and fate of N added to soil in fertilizer research is also required to better predict the amount and timing of N becoming available to crops from mineralisation of soil organic matter and manures. This is vital for several reasons. First, soil derived N makes a significant contribution to total crop N supply, commonly at least 30% of total supply in temperate regions (Macdonald et al., 1997) and averaged 79% in crops growing in tropical climates in nine countries (Dourado-Neto et al., 2010). If this quantity can be estimated more accurately in advance, fertilizer N applications can be adjusted downwards accordingly. Second, production of inorganic N from mineralisation is often poorly synchronised with crop N uptake, leading to inefficient utilisation. Intensive agricultural systems, with inevitably large inputs of nutrients, are required in regions where conditions are favourable to crop growth in order to deliver sufficient food *production* to make food *security* a reality. But for this level of production to be environmentally sustainable, more precise management of nutrient inputs to match outputs is essential. This requires progress in two areas – an ability to predict nutrient transformations and monitoring methods that are practical and usable in a wide range of situations. These requirements are valid for all nutrients but especially for N because its transformation processes occur rapidly and leakages of N to the environment are particularly problematic. Prediction of N fertilizer requirements are already aided by simple computer models of N cycle processes in some regions though these need to be greatly improved.

An ability to monitor N transformations in fields at timescales of days in periods of rapid change would greatly aid N management, helping the farmer to steer a course between avoiding yield loss through inadequate N supply and risking unnecessarily large N losses through over-supply. Whilst sampling soil to measure nitrate content is practiced in some advisory systems this is normally limited to one sampling per year before the start of the main growing period because of the labour and expense required, and typically waiting several days or weeks for the results of analyses. Two novel approaches are now becoming feasible and could be developed through further research.

(a) *Monitoring of nitrate in soil*: The development of robust and low cost solid-state ion specific electrodes that can be set in the soil and monitored as frequently as desired, certainly hourly (Miller et al., 2003). With further developments an array of such sensors could be monitored remotely using a wireless connections. If used alone the mass of data from such a system would be difficult to interpret for practical management purposes, but if combined with the use of an appropriate N cycle model such data could become invaluable, particularly if combined with other measurements such as temporal changes in soil water However, the spatial variability of such data poses challenges that have to be addressed through research to define the volume of soil influencing each measurement in addition to the general variability of soil-related data at field scale (Clark et al., 2005).

(b) *Monitoring supply of N or other nutrients through plants*: This is already practiced in some advisory systems, using light reflectance to measure chlorophyll concentration in plants (e.g. Lopez-Bellido et al., 2004) often with a monitor mounted on the tractor. Optimal N rates have been found to vary by > 100 kg N ha^{-1} at locations within a single maize field, permitting very substantial savings of N fertilizer (Kitchen et al., 2010). A far more specific and sensitive possibility is based on changes in gene expression as a plant moves from nutrient sufficiency to deficiency (Clark et al., 2005). If such nutrient-sensitive genes can be identified it is possible to introduce, by genetic modification, a construct that is influenced by promoters for the appropriate genes that control formation of reporter proteins that can easily be measured, for example by fluorescence. Hammond et al. (2003) give a proof-of-concept example for detecting P deficiency in Arabidopsis. Such "smart plants", distributed among natural versions of the same crop in the field, could be sensitive indicators of nutrient deficiency showing their signal before classical nutrient deficiency symptoms become visible. The 'smart' plants must have the same root architecture as the crop to ensure that they are accessing the same soil nutrient pools. Their development presupposes the public acceptance of at least a small number of genetically modified plants within fields.

Phosphate nutrition of crops is a clear case of "feast to famine". In regions with well developed agriculture soils sometimes contain considerably more readily available P than is required by crops. Even small losses of P to water can cause the growth of algal blooms. Such losses are often due to surface runoff, and associated with applications of animal manure. At the other extreme many soils worldwide are extremely low in plant-available P and this is a major constraint to food production (Sanchez, 2002). In soil, P is held in chemical forms having a wide range of solubilities; in general the equilibria between these forms are well understood. For practical fertilizer advice the concept of "critical values" has proved extremely valuable is. This is the soil content of plant-available P below which plant growth is inhibited when all other nutrients are non-limiting; Fig. 3 shows some examples. It has been established that maintaining P at above the critical value has no additional benefit, but for sustainable production it is essential to ensure that the soil concentration does not fall below this. Fig. 3 is based on data from long-term experiments in the UK, but there is a dearth of such data. A valuable research effort with great practical value would be to establish such sites for a range of major food crops, environments, soil types and climates worldwide.

Perennial versions of current food crops have been suggested as a contribution to more sustainable food production (Cox et al., 2006), albeit one that would require very considerable effort in plant breeding. From the viewpoint of nutrient acquisition this is likely to be beneficial: each growing season some roots would already be in place to begin absorption of nutrients. The stable root system of a perennial crop may well deliver more organic C to soil than an annual crop and, combined with elimination of annual tillage, would be expected to lead to C sequestration and improved soil physical quality. However, much plant breeding effort is required to ensure that yields currently achieved with annual crops are at least maintained.

Another possibility based on plant breeding and genetic modification is the transfer of biological nitrogen fixation into non-legume crops such as cereals. Superficially this is an attractive option, with the prospect of eliminating the need for N fertilizer. However caution is needed regarding the quantity of N likely to be fixed in relation to that required to produce large grain yields. Unkovich and Pate (2000) reviewed the amounts of N fixed by numerous legumes globally. Although there was a wide range of values, with occasional reports of 300 kg N ha^{-1} fixed within a season by soybean, values of 100 kg N ha^{-1} or less were most common. This is far less than that required for a cereal to yield in excess of 10 t ha^{-1} of grain. And presumably the N supply to such a modified crop could not be supplemented by fertilizer N as this would inhibit N fixation. In addition, it is almost certain that the diversion of photosynthate from crop growth to supplying energy to *Rhizobia* would lead to some yield penalty.

Understanding and optimising soil biological processes

Soil biological processes and populations

Biological processes are fundamental to many soil functions. The processes mediated through biological action include:

- Decomposition of organic matter (notably plant and animal residues, and organic contaminants)
- Transformation of nutrient elements, releasing them in plant-available, soluble or volatile forms, which predispose them to loss from soil (most notably nitrogen, but also phosphorus and sulphur to lesser extents)
- Mixing and formation of channels within the soil matrix by soil fauna
- Stabilisation of soil structure through the production of extracellular peptides and enmeshing filaments
- Biocontrol of soil-borne plant pathogens and pests

Organisms from a vast range of taxonomic groups are responsible for numerous transformations, though the functions and even the identities of many are unknown. The numerical size of the populations are immense; for example 10^9 bacteria g^{-1} of soil is typically quoted. But the total biomass is small, typically only a few hundred kilogramme per hectare, so living organisms are enormously "diluted" within the matrix of non-living mineral material. This dilution plus the vast taxonomic and functional diversity and complex chemical and physical interactions with non-living soil components present significant difficulties for studying soil biology. Despite these challenges, the application of conceptual models from "macroecology", and the application of modern molecular techniques have contributed to increased realisation of the massive diversity, increased understanding of the roles of individual groups of organisms, and opportunities to address how soil organisms interact to perform soil processes.

Despite the small biomass of the soil population in relation to the mass or volume of soil, it is far larger than would be predicted from knowledge of microorganisms growing under substrate-rich conditions in the laboratory. In soil the amount of energy from substrate (mainly plant roots) is extremely limited, so the organisms must be surviving under near-starvation conditions. Despite this it has been shown that the soil population maintains a high degree of "metabolic alertness", with concentrations of ATP and high values of adenylate energy charge that are typical of organisms growing exponentially *in vitro*. This is presumed to be a survival strategy developed for the harsh conditions of soil (Brookes et al., 1983; Contin et al., 2000), but is poorly understood.

Diversity-function relationships

The majority of published literature on soil biodiversity refers to semi-natural ecosystems. A search of Web of Science showed that of almost 4000 publications including soil biodiversity as key words in the last 10 years, less than one fifth were on agricultural soils. Even so, with the vast biodiversity present in all soils, a valid question posed by Wall et al. (2010) is "How much can we lose?" whilst still maintaining necessary functions. It is clear that when primary tropical forest is converted to agriculture, many groups of organisms (especially macro- and micro-fauna) are dramatically reduced in diversity in addition to population size (Wall et al., 2010 and references therein). Clearly there is potential for functions to be lost, but whether this actually occurs is less clear. Currently there is interest in linking functional traits of different groups of organisms (above- and below-ground) with different ecosystem services they may underpin as a rational means of assessing the functioning of different ecosystems (de Bello et al., 2010). This approach is promising, but it can be extremely difficult to predict impacts of population shifts resulting from management changes due to the complex interactions between biotic and abiotic factors (e.g., Cole et al., 2008). In some cases inferences can be drawn from observed changes; for example, in a manipulative experiment in grazed pasture, Parfitt et al. (2010) concluded that population changes associated with intensification could be interpreted as leading to increased risk of N losses (Parfitt et al., 2010). However Symstad et al. (2003) warn of the dangers of extrapolating biodiversity/function relationships from short-term and small-scale studies.

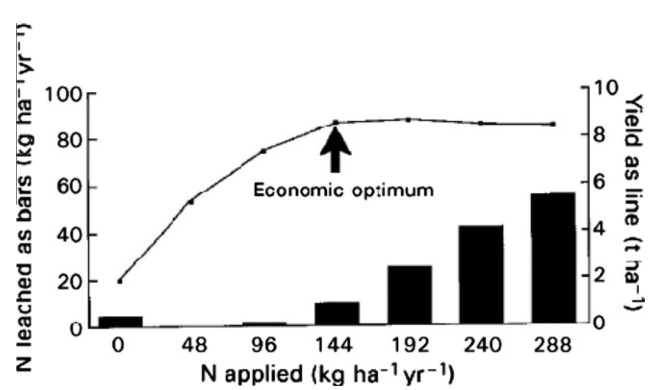

Fig. 2. A nitrogen response curve and corresponding leaching losses from the Broadbalk Experiment at Rothamsted Research, in which N treatments have been repeated on the same plots since 1843 (From Goulding (2000).

Several of the soil processes that operate to benefit crop production are carried out by a wide range of organisms and there is believed to be a high degree of functional redundancy in the community. These processes may be described as "broad" processes; they include decomposition of organic matter, some of the associated transformation of nutrient elements such as nitrogen mineralisation (releasing organic N in plant-available forms), and biological contributions to the stabilisation of soil structure (e.g., Ritz and Young, 2004). Even under harsh environmental conditions (e.g. extremes of coldness or dryness, metal contamination) leading to depressed total soil biomass, these processes can be maintained because the functions are distributed amongst a sufficiently large range of soil organisms. A recent example of resilience of organisms performing "broad" functions is a study of biodiversity in a field soil kept bare of plants for 50 years (Hirsch et al., 2009). In the absence of plant inputs the size of the microbial population measured by a variety of methods was, as expected, far smaller than in adjacent cropped soil. However, functional and genetic microbial diversity as assessed by a range of methods (substrate decomposition using Biolog; PLFAs, DNA and RNA-based analyses) was the same in the 50 year fallow and in cropped soils. Unlike the microbial population, diversity as well as abundance of soil invertebrates (mites and collembola) was sharply decreased.

By contrast to the "broad" processes, "narrow" processes are those for which the functions necessary are distributed amongst limited groups of soil organisms or only operate under a specific set of conditions. Examples include mycorrhizal associations, symbiotic nitrogen fixation, methane oxidation, nitrification, the decomposition of selected xenobiotic compounds, and antagonist interactions with plant pathogens and pests. These processes are much less resilient and more easily decreased or lost through conditions adverse to the limited groups of organisms performing them (Bardgett et al., 2005).

Not all soil processes are necessarily beneficial to crop production or soil management. For example, nitrification, a narrowly-distributed function amongst bacteria, predisposes plant-available nitrogen to loss from soil. Also, highly specific soil-borne plant pathogens can cause major economic losses. Based on macroecological concepts, there is a widely held assumption that high soil biodiversity contributes to high resilience. This probably holds for the "broad" functions, but does not necessarily hold for the "narrow" functions. It is necessary to consider the specific functions and its distribution across different groups of organisms: a trait based assessment of diversity is more informative than a taxonomically based one.

Opportunities from new methodologies

Only a small proportion (perhaps 1–10%) of the organisms in soil can be cultured under laboratory conditions, thus making studies of the population extremely difficult. Extraction of DNA and RNA from soil, and their subsequent study using molecular methods circumvents this problem. DNA gives an indication of the organisms present, though care is required as DNA can be obtained from non-viable organisms. Extraction and analysis of ribosomal RNA (rRNA) indicates the dominant active population. A large electronic database of nucleotide base sequences from the small sub-unit of rRNA, 16S for prokaryotes and 18S for eukaryotes, is expanding exponentially and provides the means to identify organisms in soil without the need for isolation and culture. There is also a rapidly increasing body of sequence data for genes encoding functions relevant to soil processes. Comparison of data with information in this growing database provides a powerful tool for identifying many soil bacteria, archaea and fungi, with varying degrees of certainty, to the genus, species or sub-species level. More precise information on which functional genes are active can be obtained from messenger RNA (mRNA), although this is technically more difficult with current methods. Methods exploiting these approaches (Hirsch et al., 2010) such as direct sequencing of nucleic acids extracted from soil and the use of microarrays could almost be regarded as a new way of classifying soils according to the range of organisms they contain, complementing traditional classifications based on particle size distribution (texture) or soil forming processes (pedogenesis). In some respects they are likely to reveal data that is uninformative: for example, confirming known trends such as certain organisms favouring certain types of soil environment (e.g. acid or alkaline, aerobic or anaerobic). However the potential is immense – some possibilities are indicated below.

Research questions of central relevance to sustainable food production and becoming amenable to elucidation using emerging understanding and new techniques

1. *Molecular basis for nitrous oxide emissions*: Bacterial reduction of nitrate is a key process leading to emissions of nitrous oxide from agricultural soils. Reduction can lead to the emission of two gases, nitrous oxide (N_2O) and dinitrogen (N_2). Whilst both represent a loss of an important nutrient, N_2O is a powerful greenhouse gas so even small changes in emission resulting from a change in agricultural management have significant environmental impacts. Some populations of denitrifying bacteria lack the nosZ gene that controls conversion of N_2O to N_2 and there are preliminary indications that the proportions of the different populations vary between soils and can be quantified using molecular techniques (Henry et al., 2006; Morales et al., 2010). If this is confirmed, it would appear to be a significant development, providing a basis for designing more effective management practices, specific for different situations, for minimising N_2O emissions from agricultural soils.
2. *Stabilisation and turnover of organic matter*: As discussed earlier, at the global scale soils contain a large fraction of the carbon in the terrestrial biosphere in the form of soil organic matter and have a crucial role as a carbon reservoir and a buffer against changing atmospheric carbon dioxide. From the viewpoint of increasing soil C storage, slowing down organic matter decomposition is a desirable objective. By contrast, organic matter decomposition is essential for recycling nutrients from plant and animal residues. Therefore, there is a conflict in objectives: stable and possibly increased organic matter reserves in soils are desirable, while breakdown of soil organic matter and the release of nutrients are simultaneously desirable. The research objective here is to discover ways of stabilising the organic skeletons of organic materials in soil organic matter, whilst allowing the release of plant nutrients.
3. *Elucidating then manipulating soil and rhizosphere populations to maximise natural biological suppression of soil-borne pathogens and pests*: Studies of naturally suppressive soils offers a potentially powerful approach to developing effective "biological control" approaches, thus decreasing reliance on pesticides. van Elsas et al. (2008) give an overview of some opportunities and Atkins et al. (2003) give a specific example of using molecular techniques in the practical application of a fungal biocontrol approach for controlling nematode pests of coffee and vegetables in Cuba.
4. *Soil ecological effects of modified plants*: Genetic modification (GM) of crops is one technique with potential to contribute to increased food security in some situations – though it is clearly not a panacea. However, there are valid questions to be addressed about the impacts on ecosystem functioning of crops having herbicide resistance or which produce insecticidal toxins. The farm-scale evaluations undertaken in the UK addressed a range of above-ground ecological questions, and found no unforeseen deleterious effects of the genetic modifications

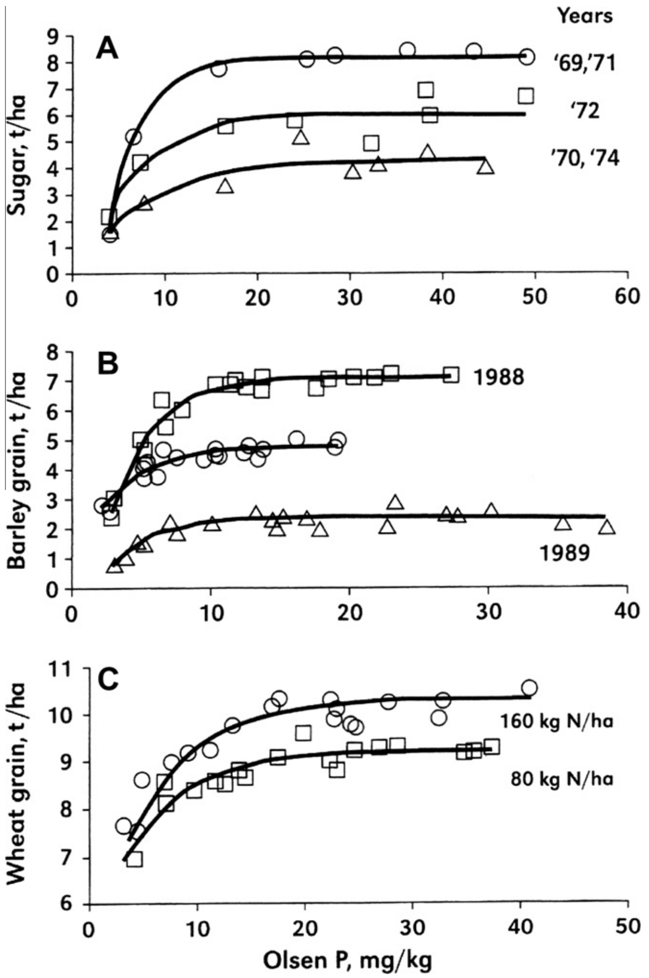

Fig. 3. Concentrations of plant-available P in soils in relation to crop yields. Data is taken from long-term field experiments in UK and illustrate the concept of "critical values". From Syers et al. (2008).

tested (Haughton et al., 2003). By contrast, to date, there have been few studies reported of below-ground ecological effects of genetically modified crops, and those effects that have been reported have been either short-lived and or lack a direct causal link between the modification and the effect. A systematic assessment of the below-ground ecological effects is needed (Lilley et al., 2006).

Root–soil interactions

Release of carbon compounds

Roots are the main driving force for all below-ground ecosystem processes because they are usually the major source of substrates and energy for microbial processes (Gregory, 2006a; Killham and Yeomans, 2001). Consequently, the microbial population density in the rhizosphere is far larger than in bulk soil and its functional diversity is subject to alteration through any shifts in the flow of C from roots. Besides the contribution to soil organic matter from senesced roots, living roots release a variety of compounds into the soil including soluble compounds (exudates), actively secreted enzymes and metallophores, and sloughed root cells (Paterson and Sim, 1999). Root exudates constitute the majority of these rhizodeposits, and are mainly composed of carbohydrates, amino acids, and organic acids together with smaller quantities of glycolipids and other phospholipids associated with plant cell membranes (Chaboud, 1983; Ostle et al., 2003; Read et al., 2003).

Structure formation

The root–soil interface is a key region for the development of soil structure through mechanisms including dispersion and aggregation of soil particles under the influence of organic carbon compounds from roots, wetting and drying, and root penetration (Dexter, 1988). This results in a more distinct and physically stable structure than in the bulk soil including the formation of rhizosheaths which adhere to the roots (Watt et al., 1994; Czarnes et al., 2000). Root hairs also play an important role in bonding soil to root surfaces (Czarnes et al., 1999; Moreno-Espindola et al., 2007), which increases contact and hence the potential uptake of water and nutrients (Pierret et al., 2007). One of the major drivers of structure formation in the rhizosphere is secondary metabolites from soil microbes. Studies using sterile soil have found that inoculation with rhizosphere colonizing microbes results in a much larger volume of soil adhering to roots that is also more structurally stable. Arbuscular mycorrhizal fungi, in part due to their filamentous structure, also influence the development of soil structure both in the rhizosphere and bulk soil (Amellal et al., 1998; Miransari et al., 2008).

Nutrients in the rhizosphere

Many studies have shown that nutrient concentrations in the rhizosphere are substantially different to those in the bulk soil as a consequence both of plant demand for nutrients and of chemical, biological and physical modifications of soil by roots (Gregory, 2006b). The selective uptake of ions at the root surface results in the frequent accumulation of some ions (e.g. calcium) and the depletion of others (e.g. nitrogen and phosphorus). Root-induced changes to the chemical environment of the rhizosphere are crucial to the nutrient acquisition of many plant species and include modifications to pH, reduction/oxidation conditions, complexation of metals and enzyme activity (Hinsinger, 1998). pH changes of 0.5–1 unit have frequently been reported within 1–2 mm of the root surface as a result of cation/anion imbalance in the uptake of plants, release of organic acids, root respiration, and microbial production of acids from root exudates (Hinsinger et al., 2003, 2005). Rhizosphere acidification by plants is common and often associated with increasing P availability and uptake. However, there are complications in interpreting the significance of this as an adaptive strategy for nutrient acquisition (Darrah, 1993; Hinsinger et al., 2005).

Some plant species (e .g. Tithonia and Crotolaria) demonstrate increased activity of acid phosphatases in the rhizosphere either directly by secretion or indirectly by stimulation of microbial activity and/or depletion of soil inorganic phosphorus (George et al., 2002). Manipulating this mechanism may provide a means for crops to access phosphate that would otherwise be unavailable, especially in regions with soils very low in plant-available P. However, some caution is needed as both the enzymes and released phosphate are subject to adsorption on mineral surfaces and competition from microbes so the benefit for the plant may be greatly decreased (George et al., 2005).

Management of the rhizosphere

There is widespread evidence for genotypic diversity in the root characteristics and compounds released from roots of many crop species (O'Toole and Bland, 1987; Gregory, 2006b). The main impetus to date for exploring root traits that might improve resource use has largely come from the need to find superior genotypes in unfavourable environments especially drought-prone regions. The traits required will differ depending on soil type and rainfall distribution. For example, Sponchiado et al. (1989) demonstrated the importance of deep rooting in common bean as an effective means of drought avoidance in the humid tropics while Brown et al. (1987) demonstrated that for barley grown in a Mediterranean climate such an approach was inappropriate because the depth of rooting was determined by the depth of wetting and the early proliferation of roots throughout the wetted profile to use water before it could evaporate from the soil surface was a more useful trait (see also Gregory et al., 2000). Ho et al. (2004) developed a quantitative model to investigate the effects of root architecture of common bean on phosphate uptake in soils of low P status. Substantial genetic variability exists for root gravitropic traits influencing the distribution of roots in the soil profile and the acquisition of resources such as P that are largely confined to moist surface layers in the tropics. This approach has been successfully used to develop improved bean genotypes for tropical soils with low P status (Lynch, 2007).

Roots are an effective means of delivering chemical compounds into soil, with possible beneficial results. One example with potential for exploitation is the release of nitrification inhibitors, with the possibility of decreasing losses of N from agricultural soils by nitrate leaching or gaseous loss. Some plants, including grasses, release natural nitrification inhibitors, resulting in biological nitrification inhibition (Subbarao et al., 2009). Delivery of nitrification inhibitors in this way may be more effective, in some situations, than the addition of chemicals to fertilizers. Given the genetic diversity found within cereal species, there is scope for further investigation of this approach.

Minimising soil erosion from agricultural land

Soil erosion presents a threat to agricultural productivity, particularly but not exclusively, in regions where agronomic inputs are low, vegetation cover is poor, soils are not resilient and where intense rainfall sometimes occurs. Highest erosion rates are often in semi-arid and tropical regions. Soil erosion is strongly affected by human impact: owing to agricultural activity, rates of soil erosion on many areas with rolling topography are 1–2 orders of magnitude greater than under natural conditions, and are now similar to those occurring in mountain areas (Montgomery, 2007).

The main agents of soil erosion are wind, water and tillage. Water erosion is most often initiated by rainfall impact degrading the surface structure of exposed soil, reducing permeability and causing the generation of surface runoff leading to sheet, rill and gully erosion. Tillage erosion refers to the redistribution of soil due to the mechanical action of tillage implements, whereas wind erosion is characteristic for lighter organic or sandy soils. Globally it is estimated that water erosion mobilizes 28 Pg yr^{-1} of soil, which together with 5 Pg yr^{-1} and 2 Pg yr^{-1} of sediment mobilized by tillage and wind erosion, respectively, gives a total flux of about 35 (±10) Pg yr^{-1} (Quinton et al., 2010): approximately 5 Mg yr^{-1} of soil for every person on our planet. Erosion does not always involve loss of soil from the land as eroded material is deposited elsewhere. Some is deposited in the terrestrial landscape, thus altering and perhaps improving soil conditions at the site of deposition. However, that which reaches surface water bodies often has serious impacts on ecosystem functioning.

In addition to obvious destruction of crops by severe rill or gulley erosion following intense rainfall, gradual erosion over long periods also causes decreased crop yields. Stocking (2003) reported yield losses ranging from 10% to 95% per 10 cm of soil loss at sites in Argentina, Brazil and Kenya. In addition to the loss of soil as a rooting medium, erosion selectively removes smaller sized particles which are enriched in nutrients and organic matter. This leads to poorer soil structure and decreased water and nutrients available to plants, reducing primary productivity. There are also significant indirect impacts of erosion on the food supply system: the destruction of infrastructure, such as rural roads, which affects access to markets and the distribution of seed and fertilizer; the contamination of rivers, impacting on fisheries and biodiversity; and the reduction of reservoir capacity due to sedimentation, which may reduce the availability of water for downstream uses including irrigation.

The mechanisms involved in soil erosion are reasonably well understood (see for example the text books, Morgan, 2005; Kirby and Morgan, 1980) and much effort has been devoted to developing models to predict erosion rates (Wischmeir and Smith, 1978; Nearing et al., 1989; Morgan et al., 1998; Wainwright et al., 2008). For many situations management practices to control or decrease erosion are well documented and demonstrated to be effective – yet they are frequently not applied. Although methods suited to local conditions are still being developed (see for example Nefzaoui and Ben Salem, 2002; Gyssels et al., 2007; Silgram et al., 2010), it is the adoption of erosion control methods rather than their availability that is lacking. The reasons for non-adoption are numerous and often complex and inter-related. They include land rights, lack of awareness of soil and water conservation, properties of the physical environment, neighbours' perceptions, poverty and the availability of labour (Gebremedhin and Swinton (2003). Facilitating change in farmer behaviour may be a matter of providing adequately resourced and effective extension services, access to appropriate technologies or funding supplies of fertilizers or other inputs or materials required for soil conservation or improved crop growth. The importance of engaging with local farmers, and learning from their knowledge, is clear especially for resource-poor subsistence farmers (e.g. Stocking, 2003). However, in many cases, the immediate benefits may be more for other land users such as those affected by sediments or lack of water downstream – or the protection of the soil resource for the sake of future food security for the wider community. This is an example of paying one group of land users for ecosystem services that primarily benefit others and raises complex policy and implementation issues. One example is making additional water available for agriculture by decreasing water losses from surface runoff, which is inexorably linked to soil erosion. It is estimated that to feed the world's population in 2030, water use in agriculture will need to be approximately doubled to 8700 km^3 yr^{-1} (Falkenmark and Rockstrom, 2006). Surface and groundwater sources will not be able to supply this volume of water; maximising infiltration and minimising water losses through runoff could provide an estimated 1200 km^3 yr^{-1} of water, which could double crop yields in Africa's semi-arid and dry subhumid savannah zone (Falkenmark and Rockstrom, 2006).

One scheme with potential for facilitating soil conservation practices is the use of Green Water Credits (GWCs) (Falkenmark and Rockstrom, 2006). These recognise the benefits of farmers retaining water in the soil rather than letting it run off, causing flooding and pollution downstream. Advice and incentives for farmers in erosion-prone upstream regions are made possible by contributions from downstream users who have a vested interest in an improved water supply. Thus one group of land users are paid for ecosystem services (increased water for irrigation) facilitated by altered land management by another group. Another example of policies to change farmer behaviour is China's ambitious "grain for green" programme. This addresses serious soil erosion in the area feeding the Yellow River by removing from annual cropping the steepest slopes which are most prone to soil erosion and establishing perennial semi-natural vegetation. Farmers are compensated for loss of production by being paid in grain and with assistance to develop alternative cropping practices on less erosion-prone land. This has been successful in decreasing sediment loading of streams (Cao et al., 2009), but has resulted in reduced water availability and a reduction in biodiversity in some areas.

A key issue in soil conservation is robust monitoring to chart the success or otherwise of specific conservation measures. Such information is required so that governments or other funders of schemes, and farmers, can be informed on whether or not the measures are being successful and deliver value for money or whether changes in policy or practice are required. At the local scale monitoring tools do exist (Stocking and Mumaghan, 2001), although they are rarely applied. Current methods for monitoring at regional scale have limitations; advances in satellite-derived information (Vrieling, 2006) and in new tracer technology (Zhang et al., 2001) offer potential for quantifying erosion, but further development is needed before they can be used with confidence.

To summarise, major needs in either practice or research are:

1. Provision of evidence for farmers and policy makers that controlling soil erosion leads to better crop yields and a more secure food supply, either directly or indirectly and in both the short- or longer-term.
2. The development and testing of locally funded mechanisms for investing in soil and water conservation and evaluating and learning from successes and failures.
3. Developing new remote sensing technologies for the targeting and monitoring the success (or failure) of soil and water conservation programmes at regional scales.

Possible beneficial impacts of biochar on soil properties and crop growth

Producing bioenergy from biomass pyrolysis offers an opportunity to genuinely sequester a portion of C in agricultural by-products as the recalcitrant char material, now termed biochar, whose natural analogues have a residence time of 1000–10,000 yrs. There is circumstantial evidence from archaeological sites in Amazonia and elsewhere that adding biochar to soil leads to the stabilisation of additional organic carbon (Liang et al., 2010). There is also some evidence, though as yet limited, that adding biochar to soil improves crop growth through increased retention of nutrients and possibly of water (Major et al., 2010). Biochar therefore has the potential to significantly alter the greenhouse gas balance of arable agriculture, whilst simultaneously maintaining physical benefits usually associated with more labile organic matter fractions. Research that demonstrates whether or not these benefits exist and, if they do, delivers a mechanistic understanding of the processes behind them, are essential if the use of biochar is to be adopted as part of an enhanced carbon offsetting strategy, in parallel to fossil fuel substitution from bioenergy (Lehmann et al., 2008; Sohi et al., 2010). But caution is required as the land use implications of widespread production and use of biochar have yet to be fully evaluated (Sutherland et al., 2010). And the evidence base for beneficial impacts of recent biochar applications, as opposed to historical applications in Amazonia, is still very small (Verheijen et al., 2009). Also, biochar can be a source of pollutants, especially persistent organic pollutants produced during pyrolysis (Shrestha et al., 2010) although when added to polluted soils it can also decrease the bioavailability of some pollutants through adsorption (Beesley et al., 2010).

Developing practices and policies

"We know more about the movement of celestial bodies than about the soil underfoot".
Leonardo da Vinci.

Great progress in the understanding of soil and its functioning has been made in the 500 years since this was stated. But many damaging mistakes in soil management have also been made, and will continue to be unless evidence-based practices are developed to meet the challenges of "sustainable intensification" (Royal Society, 2009), essential to feed the 9 billion people expected to inhabit the planet by 2050. A related challenge is to devise more effective communication and partnership approaches such that information is utilised by land managers worldwide, making it possible to produce food without causing unacceptable environmental damage, especially not worsening climate change. And without causing irreversible damage to the soil on which mankind depends.

This review has concentrated on research needs and opportunities because this was the remit of the Foresight Programme on "Global Food and Farming" of which it is a part. At various points in the review we have suggested ways to act on research findings, either through policy interventions or practical actions. Table 2 summarises these and includes suggestions of the types of action required for different aspects of knowledge and soil management. In some cases the main action is to provide information to farmers but in others specific financial incentives or regulations will be required, but the list is not definitive and new suggestions will continue to arise.

Findings from biophysical research have to be combined with knowledge of social, economic and governance issues which differ widely between nations and regions. Some applications of research are only suitable for developed regions with well-educated and/or economically prosperous farmers and a certain level of infrastructure. Others are highly relevant to small resource-poor subsistence farmers where a small change in practice could have a significant impact on livelihoods. In some instances it is possible to "jump" stages of development, e.g. the use of mobile phones to deliver market or technical information to farmers in rural regions in developing countries. Some findings are so obviously beneficial to the farmer that no particular incentive is required to promote a new practice. An example is minimum tillage in many regions of South America where innovations have often been farmer-led and the benefits to the farmer such as saving of labour, increased economic returns or soil improvement are obvious, at least for larger farmers. For small farmers there may be barriers due to the cost of changing machinery. At the other extreme, the main beneficiaries from improved nutrient management or reduced soil erosion may be people other than the farmer due to "off-site" impacts on the sediment or nutrient load in a river (as discussed in previous sections). In such cases there is likely to be a need for more concerted action at a catchment or regional scale, whether delivery of information, economic incentives or regulation. In some cases a policy action that has been beneficial for a period needs to change to reflect altered conditions. For example, in China policies including subsidies and information delivery to farmers, aimed at promoting the use of fertilizers as a contribution to national food security, have been so successful that the country now has a serious problem of nitrogen fertilizer over-use. It is clear that different policies regarding economic incentives, and perhaps regulation, are now required in order to combat serious water pollution and excessive greenhouse gas emissions.

Some areas of research covered in this review are mature and the priority is to find effective means of putting findings into practice, rather than conducting more detailed research: this is the case for controlling soil erosion. By contrast, understanding of soil biological processes is in a phase of rapid expansion due to the potential of new molecular tools when combined with more traditional understanding. From the perspective of policy and practice, the action in this area is probably to keep a "watching brief". In many cases it is likely to be some years before research findings lead to

Table 2
Summary of policies and practical actions required to develop improved soil management practices based on current knowledge and emerging research.[a]

Issue	Actions required	Policies or practices to achieve desired action	Comments
(a) Organic matter, climate change, physical properties and water			
1. Increased soil organic matter content is beneficial for almost all soil properties and functions. Even small changes in SOC[b] can have disproportionately large impacts on soil physical properties	• Encourage practices to maintain or increase SOC content in agricultural soils including return of crop residues, animal manures, other organic residues (if commensurate with human and animal health considerations).	Information to farmersIf necessary, economic incentives or regulations to promote specific practices	Increasing SOC content (depending how it is achieved) can contribute to C sequestration, thus mitigating climate change. See point 3 below
	• In LDCs[c] actions to provide energy in rural areas to decrease use of straw, dung or firewood as fuel.	Government actions and/or financial incentives	
	• Promote collection of organic "wastes" for re-use especially in peri-urban areas		
2. Reduced tillage practices (including zero tillage) can deliver improved soil structure and functioning in many (but not all) soil types and cropping systems. Benefits Include improved water infiltration and decreased erosion through increased soil C near surface and improved faunal activity	• Encourage minimum tillage where appropriate.	Information to farmersPossible economic assistance to smallest farmers to purchase new machinery	Use local data to assess applicability of reduced tillage – not always appropriate.Reduced tillage often claimed to deliver climate change benefits through soil C sequestration Be aware that these claims may be exaggerated and assess balance of soil C increase with possible increased N_2O emissions using locally relevant data
3. Soils contain large stocks of C in organic matter – can either mitigate or worsen climate change depending on whether management practices increase or decrease soil C stock	• Minimise changes in land use (especially deforestation, ploughing of grasslands, drainage of wetlands) for agricultural development – these changes cause large emissions of CO_2.	International agreements and actions by individual governments	Recognise conflict with provision of extra land for food production
	• Establish new areas of forest or other perennial plants on land that would otherwise be derelict or unused provided the change does not conflict with food production.		Recognise limitations and potential conflicts with N_2O emissions
	• Management practices to maintain or increase C stocks in agricultural soils.	Results from actions in points 1 and 2 above	
	• Practices to increase C content of subsoils.	Research required	
4. Perennial versions of current annual arable crops could deliver improvements in efficiency of use of water and nutrients, increase inputs of organic C to soil and decrease erosion	• Long term commitment to research	Funding of research and crop breeding by governments or industry	Long term goal Considerable research necessary to obtain yields currently achieved by annual crops
5. Maintaining food production with decreasing water resources – recognising water limitation to crops caused by "strong" soils[d] in addition to water shortage *per se*	• Include consideration of roots (length, distribution, signalling within plant as influenced by root/soil interactions) in crop breeding	Funding of research and crop breeding by governments or industry	
	• Maintain good soil physical conditions through maintenance of soil C and appropriate tillage	As points 1 and 2 above	
6. Minimise soil erosion through effects of water, wind and tillage	• Implement soil management and land use practices to decrease erosion – specific practices being appropriate for different situations	Information to farmers, economic incentives or regulation – depending whether main impacts are on farmers with practices favouring erosion or on others	Learn from successful schemes already implemented in some regions
(b) Crop nutrients			
7. More appropriate use of nutrients – will increase production (especially in LDCs), improve livelihoods and decrease risks of water pollution and decrease greenhouse gas emissions from agriculture. Issues generic to developed and developing countries	• Develop practical nutrient planning and management practices based on emerging research and technologies and suitable for different regions. Likely to include nutrient budget approaches, recommendation tables, simple computer-based decision support systems, sensors for measuring nutrient status of soil or crop in the field	Information to farmers	Involvement of farmers, farmer organisations and NGOs essential. In LDCs nutrient management should be part of other agronomic innovation packages
		Promotion of new approaches by industry Possible financial assistance from governments, NGOs or industry to start use of new methods in LDCs	
		Regulation required to reduce over-	Some lessons learned from N

(*continued on next page*)

Table 2 (*continued*)

Issue	Actions required	Policies or practices to achieve desired action	Comments
	• For N, apply management practices that will decrease N_2O emissions as major agricultural contribution to cutting greenhouse gas emissions • Include consideration of root characteristics in breeding and selection – different root architectures favour increased nutrient and water uptake in different environments	use or inappropriate use of fertilizers and manures in regions of nutrient sufficiency (e.g. Nitrate Vulnerable Zones as in EU) Funding of research by governments or industry	management practices and regulatory approaches in developed countries (e.g. EU, USA) can be adapted for use in LDCs. Especially relevant in rapidly developed regions (e.g. China, India, Brazil)
8. For P and K fertilization, determining "critical levels" of plant-available forms of these nutrients in soil is a priority. Will assist with increasing food production in LDCs and reduce over-supply and P pollution of water in well supplied areas. Beneficial for farmer incomes in all regions	• Set up long-term field experiments in a range of locations worldwide to establish critical soil P and K concentrations for maximum yields or relevant crops	Could be industry led or public/private partnership	Such experiments become a valuable long-term resource for wider issues of sustainability
9. Increasing nutrient supply to crops in LDCs where deficiency is key constraint to food production	• Apply current knowledge of nutrient recycling, intercropping with legumes to introduce N and deep rooted plants to capture nutrients leached to subsoil	Information to farmers and financial assistance to change practices if necessary	Learn lessons regarding holistic delivery of information from Millennium Villages Project and AGRA
	• Make fertilizers available in small quantities and at affordable prices	Schemes financed by governments, NGOs or industry – at least as a start	
(c) Soil biological processes and root/soil interactions			
10. Manage soil biological processes through increasing knowledge of processes and organisms	• Keep "watching brief" on research, especially opportunities from use of new molecular techniques. May provide new insights into decreasing N_2O emissions. Beginning to provide new approaches to identification of soil borne pests and diseases and biocontrol	Funding of research – mainly government By industry for some practical applications or new products	Be aware of potential for unintended effects on non-target organisms; need for monitoring Be aware of spurious microbial additives being marketed – seek evidence of efficacy
11. Maintain soil biodiversity to protect resilience of soil services provided by biological functions	• Apply management practices to maintain organic matter content	As for point 1	Be aware that population abundance and diversity in agricultural soil is usually less than under natural vegetation. But functional redundancy means "more is not necessarily better"
12. Using crop roots to influence soil processes offers new opportunities. E.g. increasing availability of P from soil sources; inhibiting nitrification; biocontrol applications utilising root exudates	• Research to identify beneficial traits followed by transfer to breeding/selection programmes or novel practices such as intercropping	Public or industry funding of research	Includes studies of root architecture, nutritional quality of root exudates (to influence rhizosphere organisms) and specific signal molecules
(d) Biochar			
13. Utilise influence of biochar to retain nutrients and water in soil, sequester C or beneficially alter microbial populations Possible synergy with bioenergy developments – biochar may be a low cost co-product	• Testing of emerging research results to assess whether suitable as basis for practical management strategies	Public and industry funding of research	Interesting research findings but need to critically assess evidence before committing to large scale action Evidence base is still very small

[a] Evidence and discussion regarding each issue is presented in the text under appropriate sections.
[b] SOC = soil organic carbon content, a measure of soil organic matter content.
[c] LDC = Less developed countries.
[d] Strong soils are defined as soil in which drying leads to impeded root growth – see section entitled "Optimising soil physical conditions for crop growth in a range of environments".

new management practices but it is important that policy makers and those concerned with the development of agricultural practices are alert to the potential from a rapidly developing research field. For example, molecular approaches to detecting soil borne diseases and developing biocontrol strategies are beginning to become practical, as discussed in the section on soil biological processes. Other fields of research, such as soil organic matter and nutrient management are intermediate: some aspects are mature and have already led to the development of evidence-based management practices (well applied in some instances, not at all in others) whilst other aspects (such as close monitoring of nitrate levels in soil during a crop growing season) are not yet at a practical stage for field use but could be very powerful if suitably developed.

In the near future it is likely that most rapid progress can be made at the interface between disciplines. An example is plant and soil scientists working together to develop approaches to maximise productivity in water-limited environments. There will be many other examples were progress at the interface between current traditional disciplines will be exciting and in turn these may become new disciplines in them themselves. Given the scale of the problems we face in attempting to achieve global food security it is incumbent on all concerned to look beyond our own areas to seek input from colleagues in different disciplines. Furthermore, it is essential that researchers, policy makers and practitioners in all aspects of land management and food production to communicate with each other. A key challenge is to develop effective ways of facilitating this cross-disciplinary communication, at different scales from global to local, and in a range of fora including government and inter-governmental negotiations and also discussions in local communities. It also essential that the wider environmental impacts of agricultural production, whether for food, fuel or fibre, are fully assessed in an integrated way. In view of the seriousness of the challenges of food production and numerous environmental issues such as climate change, special efforts are needed to elucidate the complex interactions and avoid unintended consequences of any course of action.

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