Gregory, A.S. and Ritz, Karl and McGrath, S.P. and Quinton, J.N. and Goulding, K.W.T. and Jones, R.J.A. and Harris, J.A. and Bol, R. and Wallace, P. and Pilgrim, E.S. and Whitmore, A.P. (2015) A review of the impacts of degradation threats on soil properties in the UK. Soil Use and Mangement, 31 (S1). pp. 1-15. ISSN 1475-2743

Gregory AS, Ritz K, McGrath SP, Quinton JN, Goulding KWT, Jones RJA, Harris JA, Bol R, Wallace P, Pilgrim ES, Whitmore AP (2015) A review of the impacts of degradation threats on soil properties in the UK. Soil Use and Management 31, 1-15.

Which has been published in final form at doi: 10.1111/sum.12212

A review of the impacts of degradation threats on soil properties in the UK

A. S. GREGORY [1], K. RITZ [2], S. P. MCGRATH [1], J. N. QUINTON [3], K. W. T. GOULDING [1], R. J. A. JONES [4], J. A. HARRIS [4], R. BOL [5], P. WALLACE [6], E. S. PILGRIM [7] & A. P. WHITMORE [1]

[1] *Department of Sustainable Soils and Grassland Systems, Rothamsted Research, Harpenden, Hertfordshire, AL5 2JQ, UK*

[2] *Division of Agricultural and Environmental Sciences, University of Nottingham, Sutton Bonington Campus, Loughborough, Leicestershire, LE12 5RD, UK*

[3] *Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK*

[4] *School of Energy, Environment and Agrifood, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK*

[5] *Terrestrial Biogeochemistry Group, Institute of Bio- and Geosciences IBG-3: Agrosphere, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*

[6] *Phil Wallace Ltd, Westland, Martlesham Heath, Ipswich, Suffolk, IP5 3SU, UK*

[7] *University of Exeter, Amory Building, Rennes Drive, Exeter, EX4 4RJ, UK*

Correspondence: A. S. Gregory. E-mail: andy.gregory@rothamsted.ac.uk

Running Title: Degradation threats to soil properties in the UK

Abstract

National governments are becoming increasingly aware of the importance of their soil resources and are shaping strategies accordingly. Implicit in any such strategy is that degradation threats and their potential effect on important soil properties and functions are defined and understood. In this paper we aimed to review the principal degradation threats on important soil properties in the UK, seeking quantitative data where possible. Soil erosion results in the removal of important topsoil and, with it, nutrients, C and porosity. A decline in soil organic matter principally affects soil biological and microbiological properties, but also impacts on soil physical properties because of the link with soil structure. Soil contamination affects soil chemical properties, affecting nutrient availability and degrading microbial properties, whilst soil compaction degrades the soil pore network. Soil sealing removes the link between the soil and most of the 'spheres', significantly affecting hydrological and microbial functions, and soils on re-developed brownfield sites are typically degraded in most soil properties. Having synthesized the literature on the impact on soil properties, we discuss potential subsequent impacts on the important soil functions, including food and fibre production, storage of water and C, support for biodiversity, and protection of cultural and archaeological heritage. Looking forward, we suggest a twin approach of field-based monitoring supported by controlled laboratory experimentation to improve our mechanistic understanding of soils. This would enable us to better predict future impacts of degradation processes, including climate change, on soil properties and functions so that we may manage soil resources sustainably.

Keywords: Soil erosion, soil organic matter, soil contamination, soil compaction, soil functions, climate change

Introduction

National governments are becoming increasingly aware of the importance of their soil resources and have begun to shape policies to recognise this. In the UK, for example, there have been soil strategies and policy documents in England (HMG, 2009b; HMG, 2011b), Scotland (Dobbie *et al.*, 2011) and Wales (WAG, 2006). All have a similar central aim, namely the ambition to manage soils sustainably and tackle potential degradation threats so that their ability to provide essential services is protected or enhanced. Soil degradation in England has been estimated to have cost the economy at least £150M - £250M each year (HMG, 2011b).

Implicit in any such strategy is that the principal degradation threats and their effect on important soil properties are defined and understood. If this can be achieved then, by extension, we may better-understand the likely impact on soil functions – the essential services that we rely on soils to perform – and we can begin to define policies to protect them. Evidence-gathering is an initial stage in the process of developing and refining policies (HMG, 2011a).

In this paper we aimed to identify and review the principal degradation threats on important soil properties in the UK, seeking quantitative data where possible. We summarize the main findings and discuss the likely subsequent impacts on soil functions and also the potential impacts of predicted changes in climate in the UK.

Methodology

Degradation threats

In examining which degradation threats were important in the context of the UK, we consulted the report of the European Environmental Assessment of Soil for Monitoring (ENVASSO) project (Huber *et al.*, 2008), which aimed to establish a soil monitoring system in support of a proposed European Union-wide Soil Framework Directive (EC, 2006). In the report of Huber *et al.* (2008), nine key threats to soil were identified: soil erosion, decline in soil organic matter (SOM), soil contamination, soil sealing, soil compaction, decline in soil biodiversity, soil salinisation, landslides and desertification. In addition, the report identified three further 'cross-cutting issues' which exist as threats to soil: climate change, land use change and brownfield development. Similar threats to soils have been identified in the UK previously (e.g. SG, 2009; HMG, 2011b).

From this list, we focused on soil erosion, decline in SOM, soil contamination, soil compaction, soil sealing, and brownfield development, as we believe these to be of the greatest relevance to soils in the UK. It is our view that the decline in soil biodiversity does not exist as a specific independent threat to soil, but that instead it arises as a result of some of the other threats identified. Similarly, land use change imparts some of the other threats identified on the soil. Therefore these two threats were covered in the context of the other threats. We review soil salinisation and landslides only briefly, as we consider these to be less important, and extremely localized in the UK. Desertification is not a threat currently to UK soils and is not reviewed. Finally we discuss climate change separately in terms of what the likely impacts might be on degradation threats and soil properties. The degradation threats considered and brief definitions are given in Table 1.

Literature review

A literature review of peer-reviewed publications was conducted using the web-based ISI Web of Knowledge ^{SM} search engine (Thomson Reuter, New York, USA), supplemented by other relevant published evidence (e.g. reports). We took each degradation threat as a search term in turn with 'soil' and 'UK' and sought data, predominantly from the 2000-2015 period, on the impacts on important soil physical, biological and chemical properties in the UK. In particular we focused on general properties likely to be of direct relevance for the ability of the soil to carry out its principal functions, including food and fibre production, water and air filtration, and biodiversity support. We synthesized the most relevant information in our review below.

The impacts of degradation threats on soil properties in the UK

Soil erosion

Although soil erosion can be natural, current concerns relate to accelerated erosion where the rate has increased significantly through human activities, and greatly exceeds current estimates of soil formation (0.3-1.4 Mg ha^{-1} $year^{-1}$ in Europe) (Verheijen *et al.*, 2009). Most erosion is by water, with light-textured soils particularly susceptible (Quinton & Catt, 2004), although wind erosion has been observed on arable soils in eastern England, albeit it is very difficult to quantify (Bullock, 1987), and peaty soils can erode at daily rates of up to 5.6 kg ha^{-1} when dry (Foulds & Warburton, 2007).

Mean annual erosion rates in England measured directly or interpreted from aerial photography on mostly arable sites are typically up to 10 Mg ha^{-1}, but can be as high as 66 Mg ha^{-1} whilst annual tillage erosion in the UK can reach 5 Mg ha^{-1} (van Oost *et al.*, 2009). Under grassland, 52% of the 399 upland sites in England and Wales surveyed by McHugh *et al.* (2002) in 1999 had suffered erosion and an estimated 89 000 m^3 of soil had been lost over an unspecified time, less than 1% of which was deposited in the same field site. Improved lowland grasslands typically have lower annual rates of erosion, ranging from 0.5-1.2 Mg ha^{-1}, (Whitmore *et al.*, 2004; Bilotta *et al.*, 2010).

Structural damage of the soil surface, caused by raindrops, running water and deposited material, reduces infiltration and increases surface runoff (Dexter, 1997; Whitmore *et al.*, 2004; Pilgrim *et al.*, 2010). The direct loss of soil C by water erosion (Lal, 2003; van Oost *et al.*, 2007) has been estimated to be 0.20-0.76 Tg annually in England and Wales (Quinton *et al.*, 2006). Plant nutrients can be lost in eroded topsoil (Pimentel *et al.*, 1995; Quinton *et al.*, 2001; Palmer & Smith, 2013), although few published studies have examined N and P losses in detail (Kronvang, 1990; Chambers *et al.*, 2000).

Decline in soil organic matter

In common with other temperate-zone countries, there has been a decline in SOM in some soils in the UK over a long period, predominantly as a result of changes in land use. Historically land has changed from native woodland to grazing land, and then on to annual arable systems. Since the 1940s, the area covered by permanent grassland has reduced and in arable systems there has been a reduction in the use of manures and an increase in cultivation depth (Bellamy *et al.*, 2005). These have all served to both reduce organic inputs and increase decomposition of existing SOM. Topsoil horizons (up to 0.30 m depth) are those most affected by SOM decline as the topsoil is the main zone affected by land use, although there is increased awareness of potential impacts of land use on subsoil SOM (e.g. Gregory *et al.*, 2014). SOM contents under arable systems are much lower than those under grass and woodland in the UK (Chapman *et al.*, 2013; Gregory *et al.*, 2014). The SOM changes as the soil adjusts to a new equilibrium of plant inputs, which can take several decades (Jenkinson *et al.*, 2008; Johnston *et al.*, 2009). Occasionally land is taken out of arable cultivation and SOM can recover, though at a much slower rate (Johnston, 1986; Poulton *et al.*, 2003; Smith *et al.*, 2007). There is conflicting evidence as to whether SOM and C stocks have declined significantly in the UK over the last 30 years where there has been no change in land use (Bellamy *et al.*, 2005; Reynolds *et al.*, 2013; Chapman *et al.*, 2013), and the current estimate of the total soil organic C stock down to 1 m depth in the whole of the UK is 5260 Tg

(Bradley *et al.*, 2005; Gregory *et al.*, 2014). Instead there is much evidence as to the effects of SOM decline on soil properties, particularly physical properties.

Specific decreases in aggregate stability of 10-40% with a 1% decrease in SOM content have been recorded in the UK and similar locations (Williams, 1971; Tisdall & Oades, 1980; Tisdall & Oades, 1982; Riley *et al.*, 2008), as well as a decrease in the resilience of soil to physical stresses, such as compaction (Watts & Dexter, 1997; Gregory *et al.*, 2009). This can lead to an undesirable domination of coarser clods (Riley *et al.*, 2008), a decrease in friability (Watts & Dexter, 1998), and a reduction in porosity (Riley *et al.*, 2008). SOM decline can reduce soil water retention (Kibblewhite *et al.*, 2008; Johnston *et al.*, 2009) by up to 10% for a difference in SOM content from 7% to 3% (Gregory *et al.*, 2009). Arable soils of low SOM content are susceptible to slumping when wetted due to aggregate instability leading to lower infiltration and greater surface runoff (Whitmore *et al.*, 2004).

The quantity and quality of SOM, as the primary food source, largely controls the soil microbial biomass (Fierer *et al.*, 2009) and biodiversity (Orwin *et al.*, 2006; Wardle *et al.*, 2006). Loss of SOM can reduce the exchange of important nutrients such as N, P and S (Johnston *et al.*, 2009). SOM loss from 5% to 2% over a 60 year period at Rothamsted resulted in a 90% decrease in microbial biomass, but no significant effect on microbial diversity (Hirsch *et al.*, 2009) or substrate utilization (Wu *et al.*, 2012). Lower fungal biomass (Gregory *et al.*, 2009) and fungal-to-bacterial biomass ratios (Bardgett *et al.*, 1996, 2007) have been found soils of low SOM content compared with undisturbed and botanically-rich grassland soils in the UK.

SOM also plays a key role in the ability of soils to buffer the effects of potentially-toxic substances, in part by chelation and adsorption (Chander & Brookes, 1993; Hund-Rinke & Kördel, 2003; Griffiths *et al.*, 2005, 2008; Kuan *et al.*, 2007). Loss of SOM can, hence, release toxic elements (ROTAP, 2009).

Soil contamination

Soil contamination may result from point or diffuse sources. Impacts of the latter are hard to predict as it can be affected by factors such as the weather, and soils far away from the source may be affected. Contamination mainly affects soil biological and chemical properties, although some contaminants (e.g. salts) may destabilize soil structure and affect soil physical properties.

Contamination that decreases soil pH, such as N deposition (NEGTAP, 2001; ROTAP, 2009), reduces nutrient availability, even at moderate levels (pH 5-7), and increases the risk of nutrient leaching (Pearson & Stewart, 1993; Jefferies & Maron, 1997; Degryse *et al.*, 2007). Soil pH is one of the main determinants of soil biodiversity and functioning (Fierer & Jackson, 2006; Smolders *et al.*, 2009; Griffiths *et al.*, 2011). Some keystone soil taxa including *Lumbricidae* (earthworms), *Collembola* (springtails), and N-fixing bacteria are particularly sensitive to metals (Emmett *et al.*, 2010). Contamination can affect the health of soil invertebrates in general (Spurgeon & Hopkin, 1996). Addition of Cu to UK soils (equivalent to 500 mg kg^{-1}) decreased both microbial respiration rates by up to 80% initially, and microbial biomass itself (Griffiths *et al.*, 2001; Kuan *et al.*, 2007; Gregory *et al.*, 2009). The effects may not be linear (Hirsch *et al.*, 1993; Giller *et al.*, 2009) as different groups dominate at different points as toxicity changes. Additions of Cu and Zn increase the metabolic quotient (Rost *et al.*, 2001) which is an indicator of microbial stress (Chander & Joergensen, 2001; Chander *et al.*, 2002). Metals added in association with sewage sludge may be more toxic than metals added as inorganic salts (Chaudri *et al.*, 2008). As a result, contamination can decrease OM mineralization (Giller *et al.*, 1998; Dai *et al.*, 2004; Emmett *et al.*, 2010), N fixation (McGrath, 1998; Broos, 2004) and the catabolic diversity of soils, measured by the soil's ability to degrade a range of compounds (Wenderoth & Reber, 1999;

Girvan *et al.*, 2005). Urban soils, often have lower biodiversity (Fountain & Hopkin, 2004; Styers *et al.*, 2010), presumably due to contamination.

Soil compaction

Compaction is mainly associated with trafficking in arable soils and livestock in grassland soils. Whereas clay soils are better-able to recover, sandy soils are particularly vulnerable (Gregory *et al.*, 2009). Subsoil compaction is particularly insidious because it is rarely detected. Recent reviews have summarized comprehensively the causes, effects (some of which are discussed below) and management of soil compaction in the UK (Clarke *et al.*, 2007; Batey, 2009).

Soil compaction degrades soil physical quality (Dexter, 1988; Whitmore & Whalley, 2009). Increases in bulk density (of up to 0.18 Mg m^{-3}, Ball *et al.*, 2008) and soil strength (of up to 3 MPa, Gregory *et al.*, 2007; Whalley *et al.*, 2008), and decreases in friability (by up to 50%, Watts & Dexter, 1998), soil porosity (by 10-25%, Mooney & Nipattasuk, 2003; Gregory *et al.*, 2009; Matthews *et al.*, 2010) and water-holding capacity (Gregory *et al.*, 2009) have been reported in UK soils. Compaction preferentially affects macropores (Breland & Hansen, 1996; Richard *et al.*, 2001) and can change the alignment of pores from vertical to parallel with respect to the soil surface (Servadio *et al.*, 2005). This affects infiltration rates (Heathwaite *et al.*, 1990; Kibblewhite *et al.*, 2008; Batey, 2009) and hence increases the risk of overland flow, flooding and erosion (Dexter, 1988). Decreases in the saturated hydraulic conductivity of soil by up to three orders of magnitude have been reported (Mooney & Nipattasuk, 2003; Matthews *et al.*, 2010). Compaction in grassland soils is less severe than in arable soil (Palmer & Smith, 2013), although it is much less understood (Bilotta *et al.*, 2007).

Compaction may have little effect on microorganisms as they inhabit small pores which are less affected (Breland & Hansen, 1996; Jensen *et al.*, 1996; Kohler *et al.*, 2005; Shestak &

Busse, 2005; Gregory *et al.*, 2007). However, microbial functions may be affected. Breland & Hansen (1996) reported reductions of up to 18% in N mineralization with compaction, ascribed to increased physical protection of SOM and microbial biomass in the smaller pores inaccessible to grazing nematodes created by compaction. Denitrification and NH_3 volatilization may increase with compaction, causing N loss (Batey & Killham, 1986). Ball *et al.* (2008) found N_2O emissions increased by up to 4 mg N m^{-2} $hour^{-1}$ following compaction – twice that of the uncompacted control. In contrast, compaction may affect soil macroorganisms. Reductions in *Collembola* (Heisler & Kaiser, 1995; Schrader & Lingnau, 1997), *Arthropoda* (arthropods) (Aritajate *et al.*, 1977a, 1977b), *Enchytraeidae* (potworms) (Schrader *et al.*, 1997; Rohrig *et al.*, 1998), and both surface-dwelling (Piearce, 1984; Radford *et al.*, 2001) and deep-burrowing *Lumbricidae* species (Rushton, 1986; Kretzschmar, 1991) have been reported.

Soil sealing

Soil sealing is associated with the main urban areas of the UK under the greatest pressure for housing and infrastructure. In 2011, 82% of the population of England lived in urban areas (ONS, 2012, 2013). Whilst there is little direct evidence of the impacts on soil properties in the UK, general impacts from a European perspective have been discussed (e.g. Huber *et al.*, 2008; Scalenghe & Marsan, 2009; Virto *et al.*, 2015). Sealing interrupts or removes completely the contact between the soil and other system components such as the biosphere, atmosphere and hydrosphere (Huber *et al.*, 2008) with significant and irreversible impacts on the ability of soil to transmit water and gas (Virto *et al.*, 2015). Declines in SOM (Wei *et al.*, 2014) and microbial biomass and respiration (Piotrowska-Dlugosz & Charzyński, 2015) have also been reported.

Brownfield development

The impact from brownfield development on soil properties is wide-ranging as determined by the specific prior engineering project. In the extreme case where brownfield development results in a non-green after-use, the soil is removed permanently and hence all soil functions will be lost. However, common brownfield developments in the UK include the restoration to a green after-use of mineral workings, landfill sites and underground infrastructure networks. In these cases, how the soil was removed, stored and reinstated prior to, during and following the lifetime of the industrial use will have a large impact on the success of the green after-use and the properties and functions of the soil.

The removal and storage of soil often has deleterious effects on soil physical properties, including compaction and loss of structure (HMG, 1996). Soil structure can be damaged with low porosity, up to 15% lower aggregate stability (Malik & Scullion, 1998), and domination of smaller (<2 mm) aggregates (Edgerton *et al.*, 1995; Gregory & Vickers, 2003, 2007). The nutrient status of the soil may be reduced due to leaching during storage and waterlogging if compacted (HMG, 1996). SOM can also be lost (Johnson *et al.*, 1988; Bentham *et al.*, 1992; Malik & Scullion, 1998; Wick *et al.*, 2009). These effects can persist when the soil is reinstated.

The high compaction and shearing forces imparted during lifting, moving and replacement of soil have immediate and significant effects on the biological community (Harris *et al.*, 1989, 1993). The soil microbial biomass can decrease by 50% immediately upon removal (Harris *et al.*, 1989) and by 95% following storage if conditions become anaerobic (Harris & Birch, 1990). *Lumbricidae* are severely affected, and their populations may take decades to recover even after the soil is reinstated. Fungi and complex organisms are disproportionately affected by engineering operations, because of their physical, multicellular structure. The observed slow recovery of microbial biomass in brownfield soils is linked to the reduced soil physical quality (Edgerton *et al.*, 1995; Harris, 2003).

Other degradation threats

Salinisation, the excess of water-soluble salts in soils by natural or human-enhanced means (Huber *et al.*, 2008), is limited to those UK soils most susceptible to seawater flooding, or naturally-occurring localised acid sulphate soils such as in East Anglia (Dent, 1985; Kibblewhite *et al.*, 2008). Salts have a deleterious effect on soil structure and often result in a release of pollutants (Du Laing *et al.*, 2009). Though more commonly associated with Mediterranean areas in Europe, particularly mountainous areas (e.g. Ferrara *et al.*, 2015; Virto *et al.*, 2015), landslides do occur in localized areas of the UK (Foster *et al.*, 2013), including coastal cliffs (Bowman & Take, 2015) and upland areas (Gunn *et al.*, 2013; Johnson & Warburton, 2015). The result of landslides is often the loss of the entire soil material and hence all properties and functions from a site. As vulnerable sites tend to be in the uplands or by the coast, there can be a significant impact on amenity and agricultural uses (Bowman & Take, 2015). Correspondingly, the soil at the deposition site is buried, severely impairing its functioning.

Discussion

The impacts of degradation threats on soil properties in the UK

From the review above, we see that the main degradation threats to soils in the UK affect a wide range of properties within the three main types: physical, biological and chemical. Soil erosion results in the removal of important topsoil and any contained nutrients, C and porosity. A decline in SOM principally affects soil biological and microbiological properties, SOM being the primary food source, but also impacts on soil physical properties because of the effect of SOM on soil structure development and stabilization. Soil contamination affects soil chemical properties, affecting nutrient availability and degrading microbial properties, whilst soil compaction degrades soil physical properties, especially soil porosity. Soil sealing removes the link between the soil and most of the ‘spheres’ and can significantly affect soil hydrological and microbial functions, but may not necessarily affect other soil properties. By contrast, soils on re-developed brownfield sites are typically degraded in physical, chemical and biological properties. From our review it is apparent that the potential or actual effect of some degradation threats on soils in the UK are well-documented, including soil erosion, decline in SOM, soil contamination and soil compaction. By contrast, the impact of soil sealing and brownfield development on soils in the UK appears to be understood less. These areas might need to be research priorities in the future if the UK population (particularly in urban areas) continues to increase.

The spatial arrangement of degradation threats to soils in the UK is complex and beyond the scope of this review. However we may offer some initial simplistic thoughts. Erosion is associated with overland flow on wet soils or wind in dry soils. Therefore in the UK upland soils in the north and west that experience considerable rainfall and arable soils of low porosity may be more prone to suffer from soil erosion by water whereas light-textured arable soils may be more prone to wind erosion, such as those in the south and east of the UK. Intuitively, soils with a greater amount of SOM have more potential to lose SOM than soils of lesser SOM. As SOM is to a large extent dictated by land use, soils under grassland, semi-natural or natural vegetation may be candidates to experience a loss of SOM, particularly if the input from vegetation changes in some way. Grassland dominates soils in the west and north of the UK, whilst the main areas of semi-natural or natural vegetation are in the uplands. However, it is important to reiterate that there is currently no definitive evidence for significant changes to SOM levels in UK soils (Bellamy *et al.*, 2005; Reynolds *et al.*, 2013; Chapman *et al.*, 2013; Gregory *et al.*, 2014). Although compaction is often perceived to be a degradation associated exclusively with trafficking of arable soils, grassland soils can become compacted from the impact of livestock, and hence compaction can potentially affect many agricultural soils in the UK. The impacts are likely to be more severe in tramlines and where livestock congregate (e.g. feeding and watering troughs) in arable and grassland systems, respectively. Soil sealing and brownfield development are primarily urban-based degradations and hence will mainly threaten soils within and surrounding the main urban areas in the UK, particularly in the cities in England. Soil contamination could also affect the same soils close to urban and industrial areas, but other contaminants, particular airborne ones, could diffuse to affect soils distant from the source. Continued development and exploitation of soil and land use spatial databases (e.g. Mackney *et al.*, 1983; Proctor *et al.*, 1998; Morton *et al.*, 2011) should help to identify soils at risk from particular degradation threats. This kind of approach can then be used to review current land management practices in order to minimize degradation impacts.

Implications for soil functions in the UK

Having synthesized the literature on the impact of degradation threats on soil properties in the UK we may then discuss the likely impacts on important soil functions – the tasks or services we ask of soil. These functions typically include food and fibre production, storage of water and C, water and air filtration, support for infrastructure, and support for biodiversity, habitats, cultural and archaeological heritage (HMG, 2011b). We discuss briefly some potential impacts of changes in soil properties arising from degradation threats on soil functions.

Loss of topsoil affects crop yields. A review of 24 studies in the UK found that yields decreased by 4% per 10 cm depth of soil loss, equivalent to a soil loss of around 100 Mg ha^{-1} (Bakker *et al.*, 2004). Erosion on lowland grasslands, which ranges from 0.5-1.2 Mg ha^{-1}, can be important locally for growth and silage quality (Bilotta *et al.*, 2010). Erosion removes soil habitat space, thus impacting on biodiversity support and water storage functions. Amenity use is also affected by erosion (Rodway-Dyer & Walling, 2010).

Degradation of soil physical properties, particularly the decrease in porosity from compaction and the destabilization of structure from loss of SOM, affect a range of soil functions. Water storage and flood regulation functions are degraded with a loss in porosity (Dexter, 1997; Whitmore *et al.*, 2004; Pilgrim *et al.*, 2010). Plant growth can decline as a result of compaction-imposed loss of porosity, particularly if a dense plough pan develops (van den Akker, 1997). Compaction impairs root penetration (Batey, 2009) and root development (Whalley *et al.*, 1995). Specific declines in crop yield have been reported in the UK (Douglas *et al.*, 1992; Gregory *et al.*, 2007), which can be up to 3 Mg ha^{-1} for each 0.1 Mg m^{-3} increase in bulk density (Whalley *et al.*, 1995) or each 1 MPa increase in strength (Whalley *et al.*, 2006, 2008). Gregory *et al.* (2007) reported yield declines of up to 3 Mg ha^{-1} in a heavily compacted loamy soil. Compaction can also increase the susceptibility of a crop to soil-borne diseases and fungi (Batey, 2009). In arable systems however some compaction is beneficial to achieve good seed-soil contact (Dexter, 1988) and to lessen the risk of lodging (Scott *et al.*, 2005).

A decline in soil physical quality has implications for biodiversity support. Plant species differ in their ability to grow in compacted soil (Godefroid & Koedam, 2004a, 2004b) and compacted grassland soils may be less biodiverse than uncompacted soils (Roovers *et al.*, 2004). Some evidence exists as to a link between compacted soil and a reduction in soil-pupating larvae of *Lepidoptera* (butterflies and moths) (Roach & Campbell, 1983). Gilroy *et* *al.* (2008) reported a negative correlation between soil strength and the abundance of *Motacilla flava* (yellow wagtail) in eastern England, perhaps related to the effect on soil-dwelling prey. Other British grassland species, including *Turdus philomelos* (song thrush), *Sturnus vulgaris* (starling) and some waders, may be similarly affected (Clarke *et al.*, 2007). The quality of soil-turf systems for amenity is impaired by compaction and trafficking (Marjamaki & Pietola, 2007; Han *et al.*, 2008), although compaction is desired in special cases, such as cricket pitches (Baker *et al.*, 1998). Compaction may affect the preservation of cultural artefacts and archaeology in the soil (Blum, 1993).

Although the quantitative evidence for critical thresholds is slight (Korschens *et al.*, 1998; Loveland & Webb, 2003; Reynolds *et al.*, 2007), there is a widely-held belief that soil cannot function optimally without an adequate level of SOM (van Camp *et al.*, 2004). Often declines in SOM and structural development are hard to separate. Robinson & Woodrun (2008) reported an inverse relationship between SOM content and surface runoff due to crusting in agricultural soils on chalk in southern England. Declines in SOM have been associated with increased erosion (Fullen, 1991) and clay dispersion (Watts & Dexter; 1998). Other functions can also be affected. Correlations have been made between SOM and the abundance of *Diptera* (flies) and aerially-active *Coleoptera* (beetles) in arable soils in England (Gilroy *et al.*, 2008) and *Culicoides impunctatus* (highland midge) in Scotland (Blackwell *et al.*, 1999). A link between SOM loss and the release of toxic elements in soils has also been found (ROTAP, 2009).

Changes in soil chemical properties, chiefly pH arising from agricultural inputs or contaminants, affect many functions. Metals and metalloids can accumulate in topsoil from either the atmosphere or the use of fertilizers, agrochemicals, manures or waste materials on land which, if released in toxic concentrations, particularly under acidifying conditions, can severely impair plant growth and food quality (Pearson & Stewart, 1993; Blake *et al.*, 1994;

Blake & Goulding, 2002; Millennium Ecosystem Assessment, 2005; Degryse *et al.*, 2007; Atkinson *et al.*, 2012). Some metals and metalloids are phytotoxic and decrease yields at high concentrations (e.g. Zn, Cu, Cr, and As), whereas 'passage poisons' affect animal and humans consuming food with little effect on yields (e.g. Cd, Mo, Se and possibly Co) (McGrath & Zhao, 2015). The UK has substantial areas that are As-contaminated (Appleton *et al.*, 2012). Acidification can cause plant nutrient imbalances (Phoenix *et al.*, 2004), increased risk of nutrient leaching (Pearson & Stewart, 1993; Jefferies & Maron, 1997; Degryse et al., 2007) and increased susceptibility of plants to stressors, including diseases and pests (Power *et al.*, 1998; Carroll *et al.*, 1999). Acid grassland can be toxic to grazing. Above-ground biomass may be significantly reduced near urban areas due, in part, to the proximity of contaminant sources (Ander *et al.*, 2013). Ground-level O_3 may also potentially reduce grass (Gonzalez *et al.*, 1999) and arable crop yields by up to 15% in the UK, in part by the effect on the ability of plants to respond to drought and to sequester C (ROTAP, 2009). Excess salt levels are toxic to most plant species, but the resulting halophytic ecosystems are often of great biodiversity value however (e.g. salt marsh, Watts *et al.*, 2003). Indeed, soil pH is one of the main determinants of plant biodiversity (Buneman *et al.*, 2006; Cookson *et al.*, 2006; Rousk *et al.*, 2009).

At a fundamental level, where soil sealing removes the link between soils and the other 'spheres', functions such as supporting vegetation growth, C sequestration, filtering water and air and supporting biodiversity are significantly or irreversibly reduced (Huber *et al.*, 2008; Scalenghe & Marsan, 2009). Also the degradations in soil properties arising from brownfield development cause problems for re-creating functioning soils. Restoration to a desired post-operation land use, such as species-rich grassland, may require intervention (Carrington & Diaz, 2011). However, modern restoration techniques can successfully recreate habitats of high nature conservation value (Tarrant *et al.*, 2013), and indeed soils with poor structure or nutrient status may help in this regard (HMG, 1996).

It is therefore apparent that if potential soil degradation threats are realized, a range of important soil functions may be affected, through their effects on measured soil properties. The studies reviewed above largely focus on functions of immediate current economic value (e.g. crop yields and water resource management), and were often empirical observations rather than mechanistic studies linked to soil properties. Extrapolation of knowledge between soil properties and soil functions is challenging as a result (HMG, 2011b) even though similar processes may be at work. A related issue is the potential or otherwise for soils to be truly multi-functional. There are obvious trade-offs: agricultural monoculture might be at odds with supporting biodiversity, for instance. In the future, a more mechanistic understanding of the response of soil functions to degradation processes, through measured changes in soil properties, would help in this regard.

It is important to note that degradation processes do not necessarily have irreversible effects on soil functions. Land management practices can be revised to reduce or even remove the degradation threat to improve soil properties and functions. Examples in agriculture include cultivation when the soil is brittle rather than plastic, and reduced tyre pressures on machinery to reduce compaction (Batey, 2009), and cultivation perpendicular to (rather than up-and-down) the slope to reduce erosion (Quinton & Catt, 2004). Farmers may also prevent SOM loss by incorporating residues or adding organic materials. On non-agricultural land, degradation threats such as contamination, sealing and brownfield site development can probably only be mitigated by policy.

The effects of climate change on soils in the UK

It is predicted that the UK will experience hotter, drier summers and warmer, wetter winters than currently, with an increased occurrence of low frequency-high magnitude events such as heat waves and intense storms (HMG, 2009a, 2009b; Lowe *et al.*, 2009). Climate change is likely to affect all the degradation threats, and hence soil properties. We briefly summarize some important implications with reference to observations in the literature and modelling. Whilst it may be possible to look at evidence from regions currently experiencing the kind of climate predicted for the UK, such soils have likely developed over millennia under stable conditions and hence may not necessarily be analogous to how UK soils will respond to rapid climate change.

Soils on the margins of stability are likely to be most vulnerable to drier summers, such as those in eastern England which already experience low rainfall, or peat soils which can suffer irreversible shrinkage upon drying. Prolonged drying can increase soil hydrophobicity (McHale *et al.*, 2005) and strength (Whitmore & Whalley, 2009). Rapid drying can increase the mobility of cationic metals (Simpson *et al.*, 2010) which can reduce the buffering capacity (Park *et al.*, 2010). The likely effect on SOM is unknown: warming may increase microbial activity (Cox *et al.*, 2002; Carney *et al.*, 2007), or net primary productivity (Smith *et al.*, 2007; Johnston *et al.*, 2009), resulting in either a net loss or gain in soil C, respectively. Some models predict significant loss of soil C across much of the UK up to 2080 (Smith *et al.*, 2005). Suseela & Dukes (2013) suggested a seasonality effect on SOM with decreased respiration during the growing season and increased respiration in the non-growing season. Global warming is predicted to cause a sea level rise of between 3-9 cm between 2010 and 2030 (Lowe *et al.*, 2009), which will increase the risk of flooding and salinisation in low-lying coastal soils of the UK.

The wet winter experienced in the UK in 2000-2001 provided some insight into future rainfall patterns (ADAS, 2002). Soils suffered from prolonged waterlogging, rill erosion, losses of NO_3 (in drainage water), S (in SO_4) and P (in sediment), and precipitation of Fe and Mn (ADAS, 2002). Waterlogging causes anaerobism and has been found to reduce N, P and K nutrient uptake rates to less than 10% of control soils, and to increase the concentration of potentially-harmful compounds including C_2H_4 (up to 6 $\mu L\ L^{-1}$) and Mn (up to 0.5 $mg\ kg^{-1}$) (Drew & Sisworo, 1979). McTiernan *et al.* (2001) reported 70-300% greater losses of dissolved organic C from seasonally-waterlogged soil compared to drained grassland, although Scholefield *et al.* (1993) found increased NO_3 leaching in drained soil at the same site. Unger *et al.* (2009) found that flooding reduced total microbial biomass, Gram-positive bacteria and mycorrhizal fungi by up to 50%. Milan (2012) reported lasting effects of high-magnitude flooding in an upland catchment in the UK where soil adjacent to the river was lost together with its vegetation. The overall increase in flood frequency in the UK may be as high as 50% at the current 50-year return period in some catchments (Kay *et al.*, 2006). The full effects of significant flooding in southern England in the winter of 2013-2014 have yet to be assessed.

Changes in soil properties arising from climate change will affect important soil functions, particularly food and fibre yields. With increased drying, rainfed agriculture could become risky for some important crops in the UK such as potato (Daccache *et al.*, 2012). Following the wet winter in the UK in 2000-2001, yields of winter wheat (12% decline), barley (7.5% decline), spring oilseed rape crop, sugar beet and potato were significantly reduced (ADAS, 2002). Rounsevell & Brignall (1994) concluded that machinery working days would be reduced should autumnal precipitation increase in England by 15%, which is entirely possible. Flooding makes it difficult to get livestock onto the land (Tyson *et al.*, 1992) and animals grazing floodplains are at risk of being lost in floodwater (Blackwell & Maltby, 2006). Whilst the greater atmospheric CO_2 may enhance yields of temperate plants (Long *et al.*, 2004) it could come at a cost of reduced plant protein content (Cotrufo *et al.*, 1998;

DaMatta *et al.*, 2010), if N becomes limited in the soil (Gill *et al.*, 2002). Further impacts on soil functions may be apparent. Increased concentrations of CO_2 may reduce plant transpiration (Korner, 2000) which could reduce the ability of the soil to store additional rainfall. Substantially reduced flows in wetlands may reduce their water regulatory capacity (Sutherland *et al.*, 2008). Waterlogging causes reducing conditions in soils which could impact on buffering and contaminant filtering (Du Laing *et al.*, 2009; Lair *et al.*, 2009). The impact of climate change on soil biodiversity remains unclear, although it will reflect changes in general soil conditions and vegetative growth. Resilience in biodiverse habitats at the larger scale may mask changes at fine scales (Fridley *et al.*, 2011). A link between climate, shrink-swell cycles in clay soils, and subsidence claims from properties damaged in the UK has been reported (Harrison *et al.*, 2012), and it is predicted that the magnitude and frequency of landslides in the UK will increase in the future (Pritchard *et al.*, 2014). There is conflicting evidence as to whether waterlogging and anaerobism will help to preserve (Caple, 1996; Raiswell, 2001) or degrade (Douteralo *et al.*, 2010) archaeological materials in soils.

It would appear that soils will need to be carefully managed in the future to minimize any exacerbating effects of climate change on the range of degradations that they currently experience.

Conclusions

With the UK as an example, we have summarized some key data on the impact of degradation threats on soil properties, and have sought to link changes in soil properties to important soil functions. The key next stage will be to continue to add to the database with field-based monitoring of broad changes to soil properties following degradation supported by controlled laboratory experimentation to improve understanding of the mechanisms involved. Outputs from such an approach, together with refinement of soil and land use spatial databases, should aid the development of models capable of extrapolating up to the national scale in order to link soil degradations to soil functions. We may also be able to predict any effect that climate change is likely to have. Armed with this, we may revise our policies so that soils are truly managed sustainably.

Acknowledgements

This review was funded by the UK Government Department for Environment, Food and Rural Affairs (Project SP1601 'Soil functions, quality and degradation – studies in support of the implementation of the Soil Strategy for England'). Rothamsted Research uses facilities funded by the UK Biotechnology and Biological Sciences Research Council.

References

ADAS 2002. The wet autumn of 2000: implications for agriculture. Project CC0372 final report. Department for Environment, Food and Rural Affairs, London, UK.

Ander, E. L., Johnson, C. C., Cave, M. R., Palumbo-Roe, B., Nathanail, C. P. & Lark, R. M. 2013. Methodology for the determination of normal contaminants in English soil background concentrations of. *Science of the Total Environment,* **454,** 604-618.

Appleton, J. D., Cave, M. R. & Wragg, J. 2012. Anthropogenic and geogenic impacts on arsenic bioaccessibility in UK topsoils. *Science of the Total Environment,* **435,** 21-29.

Aritajat, U., Madge, D. S. & Gooderham, P. T. 1977a. Effects of compaction of agricultural soils on soil fauna. 1. Field investigations. *Pedobiologia,* **17,** 262-282.

Aritajat, U., Madge, D. S. & Gooderham, P. T. 1977b. Effects of compaction of agricultural soils on soil fauna. 2. Laboratory investigations. *Pedobiologia,* **17,** 283-291.

Atkinson, N. R., Young, S. D., Tye, A. M., Breward, N. & Bailey, E. H. 2012. Does returning sites of historic peri-urban waste disposal to vegetable production pose a risk to human health? - A case study near Manchester, UK. *Soil Use and Management*, **28,** 559-570.

Baker, S. W., Cook, A. & Adams, W. A. 1998. Soil characteristics of first-class cricket pitches and their influence on playing performance. *Journal of Turfgrass Science*, **74,** 63-77.

Bakker, M. M., Govers, G. & Rounsevell, M. D. A. 2004. The crop productivity-erosion relationship: an analysis based on experimental work. *Catena*, **57,** 55-76.

Ball, B. C., Crichton, I. & Horgan, G. W. 2008. Dynamics of upward and downward N_2O and CO_2 fluxes in ploughed or no-tilled soils in relation to water-filled pore space, compaction and crop presence. *Soil & Tillage Research*, **101,** 20-30.

Bardgett, R. D., Hobbs, P. J. & Frostegard, A. 1996. Changes in soil fungal:bacterial biomass ratios following reductions in the intensity of management of an upland grassland. *Biology and Fertility of Soils*, **22,** 261-264.

Bardgett, R. D., Smith, R. S., Shiel, R. S., Tallowin, J. R. B., Mortimer, S. R., Brown, V. K., Pilgrim, E. S., Millward, D., Lawson, C., Harrison, K. A., Edwards, A. E., Hobbs, P. J., Sanderson, R., Harris, S. J., Beaumont, D. A., Murray, A. M. & Quirk, H. 2007. Diversification of grassland through the manipulation of plant-soil interactions. Project BD1451 objective 1 final report. Department for Environment, Food and Rural Affairs.

Batey, T. 2009. Soil compaction and soil management - a review. *Soil Use and Management,* **25,** 335-345.

Batey, T. & Killham, K. 1986. Field evidence on nitrogen losses by denitrification. *Soil Use and Management*, **2,** 83-86.

Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M. & Kirk, G. J. D. 2005. Carbon losses from all soils across England and Wales 1978-2003. *Nature*, **437,** 245-248.

Bentham, H., Harris, J. A., Birch, P. & Short, K. C. 1992. Habitat classification and soil restoration assessment using analysis of soil microbiological and physicochemical characteristics. *Journal of Applied Ecology,* **29,** 711-718.

Bilotta, G. S., Brazier, R. E. & Haygarth, P. M. 2007. The impacts of grazing animals on the quality of soils, vegetation, and surface waters in intensively managed grasslands. *Advances in Agronomy,* **94,** 237-280.

Bilotta, G. S., Krueger, T., Brazier, R. E., Butler, P., Freer, J., Hawkins, J. M. B., Haygarth, P. M., Macleod, C. J. A. & Quinton, J. N. 2010. Assessing catchment-scale erosion and yields of suspended solids from improved temperate grassland. *Journal of Environmental Monitoring,* **12,** 731-739.

Blackwell, A., Lock, K. A., Marshall, B., Boag, B. & Gordon, S. C. 1999. The spatial distribution of larvae of *Culicoides impunctatus* biting midges. *Medical and Veterinary Entomology,* **13,** 362-371.

Blackwell, M. S. A. & Maltby, E. (eds) 2006. *Ecoflood Guidelines: How to Use Floodplains for Flood Risk Reduction,* Office for Official Publications of the European Communities, Luxembourg.

Blake, L. & Goulding, K. W. T. 2002. Effects of atmospheric deposition, soil pH and acidification on heavy metal contents in soils and vegetation of semi-natural ecosystems at Rothamsted Experimental Station, UK. *Plant and Soil,* **240,** 235-251.

Blake, L., Johnston, A. E. & Goulding, K. W. T. 1994. Mobilization of aluminum in soil by acid deposition and its uptake by grass cut for hay - a chemical time bomb. *Soil Use and Management,* **10,** 51-55.

Blum, W. E. H. 1993. Soil protection concept of the Council of Europe and integrated soil research. In: *Integrated Soil and Sediment Research: A Basis for Proper Protection.*

(eds H. J. P. Eijsackers & T. Hamers), Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 37-47.

Bowman, E. T. & Take, W. A. 2015. The runout of chalk cliff collapses in England and France - case studies and physical model experiments. *Landslides,* **12,** 225-239.

Bradley, R. I., Milne, R., Bell, J., Lilly, A., Jordan, C. & Higgins, A. 2005. A soil carbon and land use database for the United Kingdom. *Soil Use and Management,* **21,** 363-369.

Breland, T. A. & Hansen, S. 1996. Nitrogen mineralization and microbial biomass as affected by soil compaction. *Soil Biology & Biochemistry,* **28,** 655-663.

Broos, K., Uyttebroek, M., Mertens, J. & Smolders, E. 2004. A survey of symbiotic nitrogen fixation by white clover grown on metal contaminated soils. *Soil Biology & Biochemistry,* **36,** 633-640.

Bullock, P. 1987. Soil erosion in the UK - an appraisal. *Journal of the Royal Agricultural Society of England,* **148,** 144-157.

Bunemann, E. K., Schwenke, G. D. & van Zwieten, L. 2006. Impact of agricultural inputs on soil organisms - a review. *Australian Journal of Soil Research,* **44,** 379-406.

Burghardt, W., Banko, G., Hoeke, S., Hursthouse, A., de L'Escaille, T., Ledin, S., Marsan, F. A., Sauer, D., Stahr, K., Amann, E., Quast, J., Nerger, M., Schneider, J. & Kuehn, K. 2004. Sealing soils, soils in urban areas, land use and land use planning. Report of Task Group 5, Volume VI: Research, sealing and cross-cutting issues. In: *Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection.* EUR 21319 EN/6. (eds.) L. Van-Camp, B. Bujarrabal, A.-R. Gentile, R. J. A. Jones, L. Montanarella, C. Olazabal & S.-K. Selvaradjou, Office for Official Publications of the European Communities, Luxembourg, pp. 61-107.

Caple, C. 1996. Parameters for monitoring anoxic environments. In: *Preserving Archaeological Remains 'in situ'.* (ed M. Corfield), Museum of London Archaeological Service, London, UK, pp. 113-122.

Carney, K. M., Hungate, B. A., Drake, B. G. & Megonigal, J. P. 2007. Altered soil microbial community at elevated CO_2 leads to loss of soil carbon. *Proceedings of the National Academy of Sciences of the United States of America,* **104,** 4990-4995.

Carrington, L. P. & Diaz, A. 2011. An investigation into the effect of soil and vegetation on the successful creation of a hay meadow on a clay-capped landfill. *Restoration Ecology,* **19,** 93-100.

Carroll, J. A., Caporn, S. J. M., Cawley, L., Read, D. J. & Lee, J. A. 1999. The effect of increased deposition of atmospheric nitrogen on *Calluna vulgaris* in upland Britain. *New Phytologist,* **141,** 423-431.

Chambers, B. J., Garwood, T. W. D. & Unwin, R. J. 2000. Controlling soil water erosion and phosphorus losses from arable land in England and Wales. *Journal of Environmental Quality,* **29,** 145-150.

Chander, K. & Brookes, P. C. 1993. Residual effects of zinc, copper and nickel in sewage sludge on microbial biomass in a sandy loam. *Soil Biology & Biochemistry,* **25,** 1231-1239.

Chander, K. & Joergensen, R. G. 2001. Decomposition of C-14 glucose in two soils with different amounts of heavy metal contamination. *Soil Biology & Biochemistry,* **33,** 1811-1816.

Chander, K., Klein, T., Eberhardt, U. & Joergensen, R. G. 2002. Decomposition of carbon-14-labelled wheat straw in repeatedly fumigated and non-fumigated soils with different levels of heavy metal contamination. *Biology and Fertility of Soils,* **35,** 86-91.

Chapman, S. J., Bell, J. S., Campbell, C. D., Hudson, G., Lilly, A., Nolan, A. J., Robertson, A. H. J., Potts, J. M. & Towers, W. 2013. Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. *European Journal of Soil Science,* **64,** 455-465.

Chaudri, A., McGrath, S., Gibbs, P., Chambers, B., Carlton-Smith, C., Bacon, J., Campbell, C. & Aitken, M. 2008. Population size of indigenous *Rhizobium leguminosarum* biovar *trifolii* in long-term field experiments with sewage sludge cake, metal-amended liquid sludge or metal salts: Effects of zinc, copper and cadmium. *Soil Biology & Biochemistry,* **40,** 1670-1680.

Clarke, M. A., Creamer, R. E., Deeks, L. K., Gowing, D. J. G., Holman, I. P., Jones, R. J. A., Palmer, R. C., Potts, S. G., Rickson, R. J., Ritz, K., Smith, J., Thompson, T. R. E., Truckell, I. G., Vickery, J., Whalley, W. R., Whelan, M. J. & Woodcock, B. A. 2007. Scoping study to assess soil compaction affecting upland and lowland grassland in England and Wales. Project BD2304 final report. Department for Environment, Food and Rural Affairs, London, UK.

Cookson, W. R., Marschner, P., Clark, I. M., Milton, N., Smirk, M. N., Murphy, D. V., Osman, M., Stockdale, E. A. & Hirsch, P. R. 2006. The influence of season, agricultural management, and soil properties on gross nitrogen transformations and bacterial community structure. *Australian Journal of Soil Research,* **44,** 453-465.

Cotrufo, M. F., Ineson, P. & Scott, A. 1998. Elevated CO_2 reduces the nitrogen concentration of plant tissues. *Global Change Biology,* **4,** 43-54.

Cox, J. W., Chittleborough, D. J., Brown, H. J., Pitman, A. & Varcoe, J. C. R. 2002. Seasonal changes in hydrochemistry along a toposequence of texture-contrast soils. *Australian Journal of Soil Research,* **40,** 581-604.

Cruden, D. M. & Varnes, D. J. 1996. Landslide types and processes. In: *Landslides: Investigation and Mitigation.* Special Report 247, Transportation Research Board, National Research Council. (eds.) A. K. Turner & R. L. Schuster, National Academy Press, Washington DC, USA, pp. 36-75.

Daccache, A., Keay, C., Jones, R. J. A., Weatherhead, E. K., Stalham, M. A. & Knox, J. W. 2012. Climate change and land suitability for potato production in England and Wales: impacts and adaptation. *Journal of Agricultural Science,* **150,** 161-177.

Dai, J., Becquer, T., Rouiller, J. H., Reversat, G., Bernhard-Reversat, F. & Lavelle, P. 2004. Influence of heavy metals on C and N mineralisation and microbial biomass in Zn-, Pb-, Cu-, and Cd-contaminated soils. *Applied Soil Ecology,* **25,** 99-109.

DaMatta, F. M., Grandis, A., Arenque, B. C. & Buckeridge, M. S. 2010. Impacts of climate changes on crop physiology and food quality. *Food Research International,* **43,** 1814-1823.

Degryse, F., Vlassak, V., Smolders, E. & Merckx, R. 2007. Mobilization of Cd upon acidification of agricultural soils: column study and field modelling. *European Journal of Soil Science,* **58,** 152-165.

Dent, D. 1985. An introduction to acid sulphate soils and their occurrence in East Anglia. *Seesoil (Journal of the South East England Soils Discussion Group),* **2,** 37-51.

Dexter, A. R. 1988. Advances in characterization of soil structure. *Soil & Tillage Research,* **11,** 199-238.

Dexter, A. R. 1997. Physical properties of tilled soils. *Soil & Tillage Research,* **43,** 41-63.

Dobbie, K. E., Bruneau, P. M. C. & Towers, W. (eds) 2011. *The State of Scotland's Soil,* Natural Scotland, Edinburgh, UK. pp. 187.

Douglas, J. T., Koppi, A. J. & Moran, C. J. 1992. Changes in soil structure induced by wheel traffic and growth of perennial grass. *Soil & Tillage Research,* **23,** 61-72.

Douterelo, I., Goulder, R. & Lillie, M. 2010. Soil microbial community response to land-management and depth, related to the degradation of organic matter in English wetlands: Implications for the *in situ* preservation of archaeological remains. *Applied Soil Ecology,* **44,** 219-227.

Drew, M. C. & Sisworo, E. J. 1979. Development of waterlogging damage in young barley plants in relation to plant nutrient status and changes in soil properties. *New Phytologist,* **82,** 301-314.

Du Laing, G., Rinklebe, J., Vandecasteele, B., Meers, E. & Tack, F. M. G. 2009. Trace metal behaviour in estuarine and riverine floodplain soils and sediments: A review. *Science of the Total Environment,* **407,** 3972-3985.

EC 2006. *Communication of 22 September 2006 from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions: Thematic Strategy for Soil Protection*. COM 2006, 231 final, European Commission, Brussels, Belgium, pp. 12.

Edgerton, D. L., Harris, J. A., Birch, P. & Bullock, P. 1995. Linear relationship between aggregate stability and microbial biomass in three restored soils. *Soil Biology & Biochemistry,* **27,** 1499-1501.

Emmett, B. A., Reynolds, B., Chamberlain, P. M., Rowe, E., Spurgeon, D., Brittain, S. A., Frogbrook, Z., Hughes, S., Lawlor, A. J., Poskitt, J., Potter, E., Robinson, D. A., Scott, A., Wood, C. & Woods, C. 2010. Countryside Survey: Soils Report from 2007. Technical Report No. 9/07 (CEH Project Number: C03259). Natural Environment Research Council/Centre for Ecology & Hydrology. Wallingford, Oxon., UK.

Ferrara, C., Barone, P. M. & Salvati, L. 2015. Unravelling landslide risk: soil susceptibility, agro-forest systems and the socio-economic profile of rural communities in Italy. *Soil Use and Management,* **31,** 290-298.

Fierer, N. & Jackson, R. B. 2006. The diversity and biogeography of soil bacterial communities. *Proceedings of the National Academy of Sciences of the United States of America,* **103,** 626-631.

Fierer, N., Strickland, M. S., Liptzin, D., Bradford, M. A. & Cleveland, C. C. 2009. Global patterns in belowground communities. *Ecology Letters,* **12,** 1238-1249.

Foster, C., Pennington, C. V. L., Culshaw, M. G. & Lawrie, K. 2012. The national landslide database of Great Britain: development, evolution and applications. *Environmental Earth Sciences,* **66,** 941-953.

Foulds, S. A. & Warburton, J. 2007. Wind erosion of blanket peat during a short period of surface desiccation (North Pennines, Northern England). *Earth Surface Processes and Landforms,* **32,** 481-488.

Fountain, M. T. & Hopkin, S. P. 2004. Biodiversity of Collembola in urban soils and the use of *Folsomia candida* to assess soil 'quality'. *Ecotoxicology,* **13,** 555-572.

Fridley, J. D., Grime, J. P., Askew, A. P., Moser, B. & Stevens, C. J. 2011. Soil heterogeneity buffers community response to climate change in species-rich grassland. *Global Change Biology,* **17,** 2002-2011.

Fullen, M. A. 1991. Soil organic matter and erosion processes on arable loamy sand soils in the West Midlands of England, UK. *Soil Technology,* **4,** 19-31.

Gill, R. A., Polley, H. W., Johnson, H. B., Anderson, L. J., Maherali, H. & Jackson, R. B. 2002. Nonlinear grassland responses to past and future atmospheric CO_2. *Nature,* **417,** 279-282.

Giller, K. E., Witter, E. & McGrath, S. P. 1998. Toxicity of heavy metals to microorganisms and microbial processes in agricultural soils: a review. *Soil Biology & Biochemistry,* **30,** 1389-1414.

Giller, K. E., Witter, E. & McGrath, S. P. 2009. Heavy metals and soil microbes. *Soil Biology & Biochemistry,* **41,** 2031-2037.

Gilroy, J. J., Anderson, G. Q. A., Grice, P. V., Vickery, J. A., Bray, I., Watts, P. N. & Sutherland, W. J. 2008. Could soil degradation contribute to farmland bird declines? Links between soil penetrability and the abundance of yellow wagtails *Motacilla flava* in arable fields. *Biological Conservation,* **141,** 3116-3126.

Girvan, M. S., Campbell, C. D., Killham, K., Prosser, J. I. & Glover, L. A. 2005. Bacterial diversity promotes community stability and functional resilience after perturbation. *Environmental Microbiology,* **7,** 301-313.

Godefroid, S. & Koedam, N. 2004a. Interspecific variation in soil compaction sensitivity among forest floor species. *Biological Conservation,* **119,** 207-217.

Godefroid, S. & Koedam, N. 2004b. The impact of forest paths upon adjacent vegetation: effects of the path surfacing material on the species composition and soil compaction. *Biological Conservation,* **119,** 405-419.

Gonzalez, R. C., Calleja, C. A., Arias, M. T. G., Fernandez, M. C. G. & Garcia, B. M. 1999. Decontamination of poultry meats: II. Physical treatments and the situation in the EU. *Alimentaria,* **36,** 103-111.

Gregory, A. S. & Vickers, A. W. 2003. Effects of amendments on soil structural development in a clay soil-forming material used as a cap for landfill restoration. *Soil Use and Management,* **19,** 273-276.

Gregory, A. S. & Vickers, A. W. 2007. Short-term soil development in a clay soil-forming material used as a landfill restoration cap: a case study. *Land Contamination & Reclamation,* **15,** 289-300.

Gregory, A. S., Watts, C. W., Whalley, W. R., Kuan, H. L., Griffiths, B. S., Hallett, P. D. & Whitmore, A. P. 2007. Physical resilience of soil to field compaction and the interactions with plant growth and microbial community structure. *European Journal of Soil Science,* **58,** 1221-1232.

Gregory, A. S., Watts, C. W., Griffiths, B. S., Hallett, P. D., Kuan, H. L. & Whitmore, A. P. 2009. The effect of long-term soil management on the physical and biological resilience of a range of arable and grassland soils in England. *Geoderma,* **153,** 172-185.

Gregory, A. S., Kirk, G. J. D., Keay, C. A., Rawlins, B. G., Wallace, P. & Whitmore, A. P. 2014. An assessment of subsoil organic carbon stocks in England and Wales. *Soil Use and Management,* **30,** 10-22.

Griffiths, B. S., Bonkowski, M., Roy, J. & Ritz, K. 2001. Functional stability, substrate utilisation and biological indicators of soils following environmental impacts. *Applied Soil Ecology,* **16,** 49-61.

Griffiths, B. S., Hallett, P. D., Kuan, H. L., Pitkin, Y. & Aitken, M. N. 2005. Biological and physical resilience of soil amended with heavy metal-contaminated sewage sludge. *European Journal of Soil Science,* **56,** 197-205.

Griffiths, B. S., Hallett, P. D., Kuan, H. L., Gregory, A. S., Watts, C. W. & Whitmore, A. P. 2008. Functional resilience of soil microbial communities depends on both soil structure and microbial community composition. *Biology and Fertility of Soils,* **44,** 745-754.

Griffiths, R. I., Thomson, B. C., James, P., Bell, T., Bailey, M. & Whiteley, A. S. 2011. The bacterial biogeography of British soils. *Environmental Microbiology,* **13,** 1642-1654.

Gunn, D. A., Chambers, J. E., Hobbs, P. R. N., Ford, J. R., Wilkinson, P. B., Jenkins, G. O. & Merritt, A. 2013. Rapid observations to guide the design of systems for long-term monitoring of a complex landslide in the Upper Lias clays of North Yorkshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology,* **46,** 323-336.

Han, L. B., Song, G. L. & Zhang, X. 2008. Preliminary observations on physiological responses of three turfgrass species to traffic stress. *Horttechnology,* **18,** 139-143.

Harris, J. A. 2003. Measurements of the soil microbial community for estimating the success of restoration. *European Journal of Soil Science,* **54,** 801-808.

Harris, J. A. & Birch, P. 1990. The effects of heavy civil engineering and stockpiling on the soil microbial community. *Microbiology in Civil Engineering,* **59,** 274-287.

Harris, J. A., Birch, P. & Short, K. C. 1989. Changes in the microbial community and physico-chemical characteristics of topsoils stockpiled during opencast mining. *Soil Use and Management,* **5,** 161-168.

Harris, J. A., Birch, P. & Short, K. C. 1993. Changes in the microbial community during the construction and subsequent storage of soil stockpiles: A strategist theory interpretation. *Restoration Ecology,* **1,** 88-100.

Harrison, A. M., Plim, J. F. M., Harrison, M., Jones, L. D. & Culshaw, M. G. 2012. The relationship between shrink-swell occurrence and climate in south-east England. *Proceedings of the Geologists Association,* **123,** 556-575.

Heathwaite, A. L., Burt, T. P. & Trudgill, S. T. 1990. The effect of land use on nitrogen, phosphorus and suspended sediment delivery to streams in a small catchment in southwest England. In: *Vegetation and Erosion. Processes and Environments.* (ed J. B. Thornes), John Wiley, Chichester, UK, pp. 161-178.

Heisler, C. & Kaiser, E. A. 1995. Influence of agricultural traffic and crop management on collembola and microbial biomass in arable soil. *Biology and Fertility of Soils,* **19,** 159-165.

Hirsch, P. R., Jones, M. J., McGrath, S. P. & Giller, K. E. 1993. Heavy metals from past applications of sewage sludge decrease the genetic diversity of Rhizobium leguminosarum biovar trifolii populations. *Soil Biology & Biochemistry,* **25,** 1485-1490.

Hirsch, P. R., Gilliam, L. M., Sohi, S. P., Williams, J. K., Clark, I. M. & Murray, P. J. 2009. Starving the soil of plant inputs for 50 years reduces abundance but not diversity of soil bacterial communities. *Soil Biology & Biochemistry,* **41,** 2021-2024.

HMG 1996. *Minerals Planning Guidance 7: Reclamation of Mineral Workings.* Her Majesty's Government. Office of the Deputy Prime Minister. The Stationery Office. London, UK. pp. 53.

HMG 2009a. *Adapting to Climate Change: UK Climate Projections.* Her Majesty's Government. Department for Environment, Food and Rural Affairs. Defra. London, UK. pp. 43.

HMG 2009b. *Safeguarding our Soils: A Strategy for England.* Her Majesty's Government. Department for Environment, Food and Rural Affairs. Defra. London, UK. pp. 42.

HMG 2011a. *Defra's Evidence Investment Strategy: 2010-2013 and beyond. 2011 Update.* Her Majesty's Government. Department for Environment, Food and Rural Affairs. London, UK. pp. 51.

HMG 2011b. *The Natural Choice: Securing the Value of Nature.* Her Majesty's Government. Department for Environment, Food and Rural Affairs. The Stationery Office. Norwich, UK. pp. 78.

Huber, S., Prokop, G., Arrouays, D., Banko, G., Bispo, A., Jones, R. J. A., Kibblewhite, M. G., Lexer, W., Möller, A., Rickson, R. J., Shishkov, T., Stephens, M., Toth, G., van den Akker, J. J. H., Varallyay, G., Verheijen, F. G. A. & Jones, A. R. (eds) 2008. *Environmental Assessment of Soil for Monitoring: Volume I Indicators & Criteria. EUR 23490 EN/1.,* Office for the Official Publications of the European Communities, Luxembourg.

Hund-Rinke, K. & Kördel, W. 2003. Underlying issues in bioaccessibility and bioavailability: experimental methods. *Ecotoxicology and Environmental Safety,* **56,** 52-62.

ISO 2006. *ISO11074:2005 Soil quality: Vocabulary,* International Organization for Standardization, Geneva, Switzerland.

Jefferies, R. L. & Maron, J. L. 1997. The embarrassment of riches: Atmospheric deposition of nitrogen and community and ecosystem processes. *Trends in Ecology & Evolution,* **12,** 74-78.

Jenkinson, D. S., Poulton, P. R. & Bryant, C. 2008. The turnover of organic carbon in subsoils. Part 1. Natural and bomb radiocarbon in soil profiles from the Rothamsted long-term field experiments. *European Journal of Soil Science,* **59,** 391-399.

Jensen, L. S., McQueen, D. J. & Shepherd, T. G. 1996. Effects of soil compaction on N-mineralization and microbial-C and -N .1. Field measurements. *Soil & Tillage Research,* **38,** 175-188.

Johnson, D. B., Williamson, J. C. & Bailey, A. J. 1988. Response of soil micro-organisms to stockpiling and land restoration. In: *A Seminar on Land Restoration Techniques: Ten Years of Research- What Next? Newcastle upon Tyne, UK. 18-20 July 1988.* British Coal Opencast Executive, Mansfield, UK, pp. 95-108.

Johnson, R. M. & Warburton, J. 2015. Sediment erosion dynamics of a gullied debris slide: a medium-term record. *Catena,* **127,** 152-169.

Johnston, A. E. 1986. Soil organic matter, effects on soils and crops. *Soil Use and Management,* **2,** 97-105.

Johnston, A. E., Poulton, P. R. & Coleman, K. 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy,* **101,** 1-57.

Kay, A. L., Jones, R. G. & Reynard, N. S. 2006. RCM rainfall for UK flood frequency estimation. II. Climate change results. *Journal of Hydrology,* **318,** 163-172.

Kibblewhite, M. G., Jones, R. J. A., Baritz, R., Huber, S., Arrouays, D., Micheli, E. & Stephens, M. 2008. ENVASSO Final Report Part I: Scientific and Technical Activities. ENVASSO Project (Contract 022713) coordinated by Cranfield University, UK, for Scientific Support to Policy, European Commission 6th Framewortk Research Programme.

Kohler, F., Hamelin, J., Gillet, F., Gobat, J. M. & Buttler, A. 2005. Soil microbial community changes in wooded mountain pastures due to simulated effects of cattle grazing. *Plant and Soil,* **278,** 327-340.

Korner, C. 2000. Biosphere responses to CO_2 enrichment. *Ecological Applications,* **10,** 1590-1619.

Korschens, M., Weigel, A. & Schulz, E. 1998. Turnover of soil organic matter (SOM) and long-term balances - tools for evaluating sustainable productivity of soils. *Zeitschrift fur Pflanzenernahrung und Bodenkunde,* **161,** 409-424.

Kretzschmar, A. 1991. Burrowing ability of the earthworm *Aporrectodea longa* limited by soil compaction and water potential. *Biology and Fertility of Soils,* **11,** 48-51.

Kronvang, B. 1990. Sediment-associated phosphorus transport from two intensively farmed catchment areas. In: *Soil Erosion on Agricultural Land.* eds J. Boardman, L. D. L. Foster & J. A. Dearing), John Wiley, Chichester, UK, pp. 313-330.

Kuan, H. L., Hallett, P. D., Griffiths, B. S., Gregory, A. S., Watts, C. W. & Whitmore, A. P. 2007. The biological and physical stability and resilience of a selection of Scottish soils to stresses. *European Journal of Soil Science,* **58,** 811-821.

Lair, G. J., Zehetner, F., Fiebig, M., Gerzabek, M. H., van Gestel, C. A. M., Hein, T., Hohensinner, S., Hsu, P., Jones, K. C., Jordan, G., Koelmans, A. A., Poot, A., Slijkerman, D. M. E., Totsche, K. U., Bondar-Kunze, E. & Barth, J. A. C. 2009. How do long-term development and periodical changes of river-floodplain systems affect the fate of contaminants? Results from European rivers. *Environmental Pollution,* **157,** 3336-3346.

Lal, R. 2003. Soil erosion and the global carbon budget. *Environment International,* **29,** 437-450.

Long, S. P., Ainsworth, E. A., Rogers, A. & Ort, D. R. 2004. Rising atmospheric carbon dioxide: plants face the future. *Annual Review of Plant Biology,* **55,** 591-628.

Loveland, P. & Webb, J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil & Tillage Research,* **70,** 1-18.

Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. & Bradley, S. 2009. UK Climate Projections Science Report: Marine and Coastal Projections. Met Office Hadley Centre, Exeter, UK.

Mackney, D., Hodgson, J. M., Hollis, J. M. & Staines, S. J. 1983. *The 1:250000 National Soil Map of England and Wales*. Soil Survey of England and Wales, Harpenden, UK.

Malik, A. & Scullion, J. 1998. Soil development on restored opencast coal sites with particular reference to organic matter and aggregate stability. *Soil Use and Management,* **14,** 234-239.

Marjamaki, T. & Pietola, L. 2007. Root growth dynamics in golf greens with different compression intensities and winter survival. *Agricultural and Food Science,* **16,** 66-76.

Matthews, G. P., Laudone, G. M., Gregory, A. S., Bird, N. R. A., Matthews, A. G. d. G. & Whalley, W. R. 2010. Measurement and simulation of the effect of compaction on the pore structure and saturated hydraulic conductivity of grassland and arable soil. *Water Resources Research,* **46,** W05501.

McGrath, S. P. 1998. Phytoextraction for soil remediation. In: *Plants That Hyperaccumulate Heavy Metals: Their Role in Phytoremediation, Microbiology, Archaeology, Mineral Exploration and Phytomining.* (ed R. R. Brooks), CABI, Wallingford, UK, pp. 261-287.

McGrath, S.P. & Zhao, F.J. 2015. Concentrations of metals and metalloids in soils that have the potential to lead to exceedance of maximum limit concentrations of contaminants in food and feed. *Soil Use and Management,* **in press**.

McHale, G., Newton, M. I. & Shirtcliffe, N. J. 2005. Water-repellent soil and its relationship to granularity, surface roughness and hydrophobicity: a materials science view. *European Journal of Soil Science,* **56,** 445-452.

McHugh, M., Harrod, T. & Morgan, R. 2002. The extent of soil erosion in upland England and Wales. *Earth Surface Processes and Landforms,* **27,** 99-107.

McTiernan, K. B., Jarvis, S. C., Scholefield, D. & Hayes, M. H. B. 2001. Dissolved organic carbon losses from grazed grasslands under different management regimes. *Water Research,* **35,** 2565-2569.

Met Office 2015. *What is climate change?* [Online] Available at: http://www.metoffice.gov.uk/climate-guide/climate-change; accessed 01/05/2015.

Milan, D. J. 2012. Geomorphic impact and system recovery following an extreme flood in an upland stream: Thinhope Burn, northern England, UK. *Geomorphology,* **138,** 319-328.

Millennium Ecosystem Assessment 2005. *Ecosystems and Human Well-Being: Current States and Trends,* Island Press, Washington DC, USA.

Mooney, S. J. & Nipattasuk, W. 2003. Quantification of the effects of soil compaction on water flow using dye tracers and image analysis. *Soil Use and Management*, **19,** 356-363.

Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Wadsworth, R. & Simpson, I. C. 2011. *Final Report for LCM2007 - the new UK Land Cover Map.* Countryside Survey Technical Report No. 11/07. CEH Project No. C03259. Natural Environment Research Council/Centre for Ecology & Hydrology, Wallingford, Oxon, UK. pp. 112.

NEGTAP 2001. *Transboundary Air Pollution: Acidification, Eutrophication and Ground-Level Ozone in the UK*. National Expert Group on Transboundary Air Pollution at CEH Edinburgh on behalf of the UK Department for Environment, Food and Rural Affairs, Scottish Executive, the National Assembly for Wales / Cynulliad Cenedlaethol Cymru, Department of the Environment for Northern Ireland. [Online] Available at: http://uk-air.defra.gov.uk/library/reports?report_id=109; accessed: 01/01/2014.

ONS 2012. *2011 Census. Population and Household Estimates for England and Wales*. Office for National Statistics. pp. 36. [Online] Available at: http://www.ons.gov.uk/ons/dcp171778_270487.pdf; accessed 24/07/2014.

ONS 2013. *2011 Census Analysis. Comparing Rural and Urban Areas of England and Wales*. Office for National Statistics. pp. 43. [Online] Available at: http://www.ons.gov.uk/ons/rel/census/2011-census-analysis/rural-urban-analysis/comparing-rural-and-urban-areas-of-england-and-wales.html; accessed 24/07/2014.

Orwin, K. H., Wardle, D. A. & Greenfield, L. G. 2006. Ecological consequences of carbon substrate identity and diversity in a laboratory study. *Ecology,* **87,** 580-593.

Palmer, R. C. & Smith, R. P. 2013. Soil structural degradation in SW England and its impact on surface-water runoff generation. *Soil Use and Management,* **29,** 567-575.

Park, J., Duan, L., Kim, B., Mitchell, M. J. & Shibata, H. 2010. Potential effects of climate change and variability on watershed biogeochemical processes and water quality in Northeast Asia. *Environment International,* **36,** 212-225.

Pearson, J. & Stewart, G. R. 1993. The deposition of atmospheric ammonia and its effects on plants. *New Phytologist,* **125,** 283-305.

Phoenix, G. K., Booth, R. E., Leake, J. R., Read, D. J., Grime, J. P. & Lee, J. A. 2004. Simulated pollutant nitrogen deposition increases P demand and enhances root-surface phosphatase activities of three plant functional types in a calcareous grassland. *New Phytologist,* **161,** 279-289.

Piearce, T. G. 1984. Earthworm populations in soils disturbed by trampling. *Biological Conservation,* **29,** 241-252.

Pilgrim, E. S., Macleod, C. J. A., Blackwell, M. S. A., Bol, R., Hogan, D. V., Chadwick, D. R., Cardenas, L., Misselbrook, T. H., Haygarth, P. M., Brazier, R. E., Hobbs, P., Hodgson, C., Jarvis, S., Dungait, J., Murray, P. J. & Firbank, L. G. 2010. Interactions among agricultural production and other ecosystem services delivered from European temperate grassland systems. *Advances in Agronomy,* **109,** 117-154.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., Ncnair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. & Blair, R. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science,* **267,** 1117-1123.

Piotrowska-Dlugosz, A. & Charzyński, P. 2015. The impact of the soil sealing degree on microbial biomass, enzymatic activity, and physicochemical properties in the Ekranic Technosols of Toruń (Poland). *Journal of Soils and Sediments,* **15,** 47-59.

Poulton, P. R., Pye, E., Hargreaves, P. R. & Jenkinson, D. S. 2003. Accumulation of carbon and nitrogen by old arable land reverting to woodland. *Global Change Biology,* **9,** 942-955.

Power, S. A., Ashmore, M. R. & Cousins, D. A. 1998. Impacts and fate of experimentally enhanced nitrogen deposition on a British lowland heath. *Environmental Pollution,* **102,** 27-34.

Pritchard, O. G., Hallett, S. H. & Farewell, T. S. 2014. Soil impacts on UK infrastructure: current and future climate. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability,* **167,** 170-184.

Proctor, M. E., Siddons, P. A., Jones, R. J. A., Bellamy, P. H. & Keay, C. A. 1998. LandIS - a land information system for the UK. In: *Land Information Systems: Developments for Planning the Sustainable Use of Land Resources.* European Soil Bureau Research Report No. 4. EUR 17729 EN (eds. H. J. Heineke, W. Eckelmann, A. J. Thomasson, R. J. A. Jones, L. Montanarella & B. Buckley), Office for Official Publications of the European Communities, Luxembourg, pp. 219–233.

Quinton, J. N. & Catt, J. A. 2004. The effects of minimal tillage and contour cultivation on surface runoff, soil loss and crop yield in the long-term Woburn Erosion Reference Experiment on sandy soil at Woburn, England. *Soil Use and Management*, **20,** 343-349.

Quinton, J. N., Catt, J. A. & Hess, T. M. 2001. The selective removal of phosphorus from soil: Is event size important? *Journal of Environmental Quality*, **30,** 538-545.

Quinton, J. N., Catt, J. A., Wood, G. A. & Steer, J. 2006. Soil carbon losses by water erosion: Experimentation and modeling at field and national scales in the UK. *Agriculture Ecosystems & Environment*, **112,** 87-102.

Radford, B. J., Wilson-Rummenie, A. C., Simpson, G. B., Bell, K. L. & Ferguson, M. A. 2001. Compacted soil affects soil macrofauna populations in a semi-arid environment in central Queensland. *Soil Biology & Biochemistry,* **33,** 1869-1872.

Raiswell, R. 2001. Defining the burial environment. In: *Handbook of Archaeological Sciences.* eds D. R. Brothwell & A. M. Pollard), John Wiley & Sons Ltd, Chichester, UK, pp. 595-603.

Reynolds, W. D., Drury, C. F., Yang, X. M., Fox, C. A., Tan, C. S. & Zhang, T. Q. 2007. Land management effects on the near-surface physical quality of a clay loam soil. *Soil & Tillage Research,* **96,** 316-330.

Reynolds, B., Chamberlain, P. M., Poskitt, J., Woods, C., Scott, W. A., Rowe, E. C., Robinson, D. A., Frogbrook, Z. L., Keith, A. M., Henrys, P. A., Black, H. I. J. & Emmett, B. A. 2013. Countryside survey: national "soil change" 1978-2007 for topsoils in Great Britain - acidity, carbon, and total nitrogen status. *Vadose Zone Journal,* **12,** 0114.

Richard, G., Cousin, I., Sillon, J. F., Bruand, A. & Guerif, J. 2001. Effect of compaction on the porosity of a silty soil: influence on unsaturated hydraulic properties. *European Journal of Soil Science,* **52,** 49-58.

Riley, H., Pommeresche, R., Eltun, R., Hansen, S. & Korsaeth, A. 2008. Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. *Agriculture Ecosystems & Environment,* **124,** 275-284.

Roach, S. H. & Campbell, R. B. 1983. Effects of soil compaction on bollworm (Lepidoptera: Noctuidae) moth emergence. *Environmental Entomology,* **12,** 1882-1886.

Robinson, D. A. & Woodun, J. K. 2008. An experimental study of crust development on chalk downland soils and their impact on runoff and erosion. *European Journal of Soil Science,* **59,** 784-798.

Rodway-Dyer, S. J. & Walling, D. E. 2010. The use of Cs-137 to establish longer-term soil erosion rates on footpaths in the UK. *Journal of Environmental Management,* **91,** 1952-1962.

Rohrig, R., Langmaack, M., Schrader, S. & Larink, O. 1998. Tillage systems and soil compaction - their impact on abundance and vertical distribution of Enchytraeidae. *Soil & Tillage Research,* **46,** 117-127.

Roovers, P., Baeten, S. & Hermy, M. 2004. Plant species variation across path ecotones in a variety of common vegetation types. *Plant Ecology,* **170,** 107–119.

Rost, U., Joergensen, R. G. & Chander, K. 2001. Effects of Zn enriched sewage sludge on microbial activities and biomass in soil. *Soil Biology & Biochemistry,* **33,** 633-638.

ROTAP 2009. *Review of Transboundary Air Pollution. Acidification, Eutrophication, Ground Level Ozone and Heavy Metals in the UK.* Complete ROTAP Report. Centre for Ecology and Hydrology, Penicuik, UK. [Online] Available at: http://www.rotap.ceh.ac.uk; accessed 01/01/2014.

Rounsevell, M. D. A. & Brignall, A. P. 1994. The potential effects of climate change on autumn soil tillage opportunities in England and Wales. *Soil & Tillage Research,* **32,** 275-289.

Rousk, J., Brookes, P. C. & Baath, E. 2009. Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. *Applied and Environmental Microbiology,* **75,** 1589-1596.

Rushton, S. P. 1986. The effects of soil compaction on *Lumbricus terrestris* and its possible implications for populations on land reclaimed from open-cast coal mining. *Pedobiologia,* **29,** 85-90.

Scalenghe, R. & Marsan, F. A. 2009. The anthropogenic sealing of soils in urban areas. *Landscape and Urban Planning,* **90,** 1-10.

Scholefield, D., Tyson, K. C., Garwood, E. A., Armstrong, A. C., Hawkins, J. & Stone, A. C. 1993. Nitrate leaching from grazed grassland lysimeters: effects of fertilizer input, field drainage, age of sward and patterns of weather. *Journal of Soil Science,* **44,** 601-613.

Schrader, S. & Lingnau, M. 1997. Influence of soil tillage and soil compaction on microarthropods in agricultural land. *Pedobiologia,* **41,** 202-209.

Schrader, S., Langmaack, M. & Helming, K. 1997. Impact of Collembola and enchytraeidae on soil surface roughness and properties. *Biology and Fertility of Soils,* **25,** 396-400.

Scott, D. I., Tams, A. R., Berry, P. M. & Mooney, S. J. 2005. The effects of wheel-induced soil compaction on anchorage strength and resistance to root lodging of winter barley (*Hordeum vulgare* L.). *Soil & Tillage Research,* **82,** 147-160.

Servadio, P., Marsili, A., Vignozzi, N., Pellegrini, S. & Pagliai, M. 2005. Effects on some soil qualities in central Italy following the passage of four wheel drive tractor fitted with single and dual tires. *Soil & Tillage Research,* **84,** 87-100.

SG 2009. *The Scottish Soil Framework,* The Scottish Government, Edinburgh, UK, pp. 64.

Shestak, C. J. & Busse, M. D. 2005. Compaction alters physical but not biological indices of soil health. *Soil Science Society of America Journal,* **69,** 236-246.

Simpson, S. L., Fitzpatrick, R. W., Shand, P., Angel, B. M., Spadaro, D. A. & Mosley, L. 2010. Climate-driven mobilisation of acid and metals from acid sulfate soils. *Marine and Freshwater Research,* **61,** 129-138.

Smith, J., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R. J. A., Montanarella, L., Rounsevell, M. D. A., Reginster, I. & Ewert, F. 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. *Global Change Biology,* **11,** 2141-2152.

Smith, P., Chapman, S. J., Scott, W. A., Black, H. I. J., Wattenbach, M., Milne, R., Campbell, C. D., Lilly, A., Ostle, N., Levy, P. E., Lumsdon, D. G., Millard, P., Towers, W., Zaehle, S. & Smith, J. U. 2007. Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978-2003. *Global Change Biology*, **13,** 2605-2609.

Smolders, E., Oorts, K., van Sprang, P., Schoeters, I., Janssen, C. R., McGrath, S. P. & McLaughlin, M. J. 2009. Toxicity of trace metals in soil as affected by soil type and aging after contamination: using calibrated bioavailability models to set ecological soil standards. *Environmental Toxicology and Chemistry,* **28,** 1633-1642.

Spurgeon, D. J. & Hopkin, S. P. 1996. Effects of metal-contaminated soils on the growth, sexual development, and early cocoon production of the earthworm *Eisenia fetida*, with particular reference to zinc. *Ecotoxicology and Environmental Safety,* **35,** 86-95.

Styers, D. M., Chappelka, A. H., Marzen, L. J. & Somers, G. L. 2010. Developing a land-cover classification to select indicators of forest ecosystem health in a rapidly urbanizing landscape. *Landscape and Urban Planning,* **94,** 158-165.

Suseela, V. & Dukes, J. S. 2013. The responses of soil and rhizosphere respiration to simulated climatic changes vary by season. *Ecology,* **94,** 403-413.

Sutherland, W. J., Bailey, M. J., Bainbridge, I. P., Brereton, T., Dick, J. T. A., Drewitt, J., Dulvy, N. K., Dusic, N. R., Freckleton, R. P., Gaston, K. J., Gilder, P. M., Green, R. E., Heathwaite, A. L., Johnson, S. M., Macdonald, D. W., Mitchell, R., Osborn, D., Owen, R. P., Pretty, J., Prior, S. V., Prosser, H., Pullin, A. S., Rose, P., Stott, A., Tew, T., Thomas, C. D., Thompson, D. B. A., Vickery, J. A., Walker, M., Walmsley, C., Warrington, S., Watkinson, A. R., Williams, R. J., Woodroffe, R. & Woodroof, H. J. 2008. Future novel threats and opportunities facing UK biodiversity identified by horizon scanning. *Journal of Applied Ecology,* **45,** 821-833.

Tarrant, S., Ollerton, J., Rahman, M. L., Tarrant, J. & McCollin, D. 2013. Grassland Restoration on Landfill Sites in the East Midlands, United Kingdom: An Evaluation of Floral Resources and Pollinating Insects. *Restoration Ecology,* **21,** 560-568.

Tisdall, J. M. & Oades, J. M. 1980. The effect of crop rotation on aggregation in a red brown earth. *Australian Journal of Soil Research,* **18,** 423-433.

Tisdall, J. M. & Oades, J. M. 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science,* **33,** 141-163.

Tyson, K. C., Garwood, E. A., Armstrong, A. C. & Scholefield, D. 1992. Effects of field drainage on the growth of herbage and the liveweight gain of grazing beef cattle. *Grass and Forage Science,* **47,** 290-301.

Unger, I. M., Kennedy, A. C. & Muzika, R. M. 2009. Flooding effects on soil microbial communities. *Applied Soil Ecology,* **42,** 1-8.

van Camp, N., vande Walle, I., Mertens, J., De Neve, S., Samson, R., Lust, N., Lemeur, R., Boeckx, P., Lootens, P., Beheydt, D., Mestdagh, I., Sleutel, S., Verbeeck, H., van Cleemput, O., Hofman, G. & Carlier, L. 2004. Inventory-based carbon stock of Flemish forests: comparison of European biomass expansion factors. *Annals of Forest Science,* **61,** 677-682.

van den Akker, J. J. H. 1997. Construction of a wheel-load bearing capacity map of the Netherlands. In: *Proceedings of the 14th International Soil Tillage Research Organization Conference, Pulawy, Poland, 27 July - 01 August 1997. Bibliotheca Fragmenta Agronomica.* pp. 15-18.

van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., Kosmas, C., Giraldez, J. V., da Silva, J. R. M. & Merckx, R. 2007. The impact of agricultural soil erosion on the global carbon cycle. *Science,* **318,** 626-629.

van Oost, K., Cerdan, O. & Quine, T. A. 2009. Accelerated sediment fluxes by water and tillage erosion on European agricultural land. *Earth Surface Processes and Landforms,* **34,** 1625-1634.

Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J. & Smith, C.J. 2009. Tolerable versus actual soil erosion rates in Europe. *Earth Science Reviews*, **94,** 23-38.

Virto, I., Imaz, M. J., Fernández-Ugalde, O., Gartzia-Bengoetxea, N., Enrique, A. & Bescansa, P. 2015. Soil degradation and soil quality in Western Europe: current situation and future perspectives. *Sustainability,* **7,** 313-365.

WAG 2006. *Environment Strategy for Wales*, Welsh Assembly Government, Cardiff, UK, pp. 70.

Wardle, D. A., Yeates, G. W., Barker, G. M. & Bonner, K. I. 2006. The influence of plant litter diversity on decomposer abundance and diversity. *Soil Biology & Biochemistry,* **38,** 1052-1062.

Watts, C. W. & Dexter, A. R. 1997. The influence of organic matter in reducing the destabilization of soil by simulated tillage. *Soil & Tillage Research,* **42,** 253-275.

Watts, C. W. & Dexter, A. R. 1998. Soil friability: theory, measurement and the effects of management and organic carbon content. *European Journal of Soil Science,* **49,** 73-84.

Watts, C. W., Tolhurst, T. J., Black, K. S. & Whitmore, A. P. 2003. In situ measurements of erosion shear stress and geotechnical shear strength of the intertidal sediments of the experimental managed realignment scheme at Tollesbury, Essex, UK. *Estuarine Coastal and Shelf Science,* **58,** 611-620.

Wei, Z., Wu, S., Yan, X. & Zhou, S. 2014. Density and stability of soil organic carbon beneath impervious surfaces in urban areas. *PLoS One,* **9,** e109380.

Wenderoth, D. F. & Reber, H. H. 1999. Correlation between structural diversity and catabolic versatility of metal-affected prototrophic bacteria in soil. *Soil Biology & Biochemistry,* **31,** 345-352.

Whalley, W. R., Dumitru, E. & Dexter, A. R. 1995. Biological effects of soil compaction. *Soil & Tillage Research,* **35,** 53-68.

Whalley, W. R., Clark, L. J., Gowing, D. J. G., Cope, R. E., Lodge, R. J. & Leeds-Harrison, P. B. 2006. Does soil strength play a role in wheat yield losses caused by soil drying? *Plant and Soil,* **280,** 279-290.

Whalley, W. R., Watts, C. W., Gregory, A. S., Mooney, S. J., Clark, L. J. & Whitmore, A. P. 2008. The effect of soil strength on the yield of wheat. *Plant and Soil,* **306,** 237-247.

Whitmore, A. P. & Whalley, W. R. 2009. Physical effects of soil drying on roots and crop growth. *Journal of Experimental Botany,* **60,** 2845-2857.

Whitmore, A. P., Rickson, R. J., Watts, C. W. & Clarke, M. A. 2004. Critical levels of soil organic carbon in surface soils in relation to soil stability, function and infiltration. Project SP0519 final report. Department for Environment, Food and Rural Affairs, London, UK.

Wick, A. F., Stahl, P. D., Ingram, L. J. & Vicklund, L. 2009. Soil aggregation and organic carbon in short-term stockpiles. *Soil Use and Management,* **25,** 311-319.

Williams, R. J. B. 1971. Relationships between the composition of soils and physical measurements made on them. In: *Rothamsted Experimental Station. Report for 1970. Part 2.* Rothamsted Experimental Station, Harpenden, UK, pp. 5-35.

Wu, Y., Kemmitt, S., White, R. P., Xu, J. & Brookes, P. C. 2012. Carbon dynamics in a 60 year fallowed loamy-sand soil compared to that in a 60 year permanent arable or permanent grassland UK soil. *Plant and Soil,* **352,** 51-63.

Table 1 The eight degradation threats identified as important for soils in the UK. The descriptions are those of Huber *et al.* (2008), unless stated otherwise.

Degradation threat	Brief description
Soil erosion	The accelerated loss of soil as a result of anthropogenic activity in excess of accepted rates of natural soil formation.
Decline in soil organic matter	The negative imbalance between the build-up of soil organic matter and rates of decomposition, leading to an overall decline in soil organic matter content and/or quality.
Soil contamination	The presence of a substance or agent in the soil as a result of human activity emitted from moving sources, from sources with a large area, or from many sources (diffuse) (ISO, 2006), or where intensive industrial activities, inadequate waste disposal, mining, military activities or accidents introduce excessive amounts of contaminants (local).
Soil compaction	The densification and distortion of soil by which total and air-filled porosity are reduced.
Soil sealing	The destruction or covering of soil by buildings, constructions and layers or other bodies of artificial material which may be very slowly permeable to water (Burghardt *et al.*, 2004).
Brownfield development	The further development of developed land previously used for commercial or industrial purposes, including restoration of green after-uses.
Soil salinisation	The excessive increase of water-soluble salts in soil through natural processes and human interventions.
Landslides	The movement of a mass of rock, debris, artificial fill or soil

	down a slope under the force of gravity (Cruden & Varnes, 1996).
Climate change	The large-scale, long-term shift in the planet's weather patterns or average temperatures (Met Office, 2015).