A review of climate change impacts on urban soil functions with examples and policy insights from England, UK.

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Abstract

As of 2010, more than half of the global population resides in urban areas and relies to some extent on the functions, services and natural capital provided by urban soils. Greater extremes in climate predicted for the coming decades will impact on these urban soil functions to varying degrees. We provide an inventory of urban soil functions based on an extension to the typology of the Millennium Ecosystem Assessment (i.e. we added a 'carrying function' to those of supporting, regulating, provisioning and cultural functions) and review the climate drivers which are likely to have the most significant impacts upon them, using urban soils of England as an exemplar. We identify knowledge gaps, as in areas such as carbon cycling and storage, disease regulation and cultural services. We assess adaptation measures which may ameliorate these potential, climate-change related impacts including changes in construction practices, developments in green architecture and development proposals under the planning regime. We discuss the lack of policies relating to urban soils and the problem associated with monitoring their functions, as is often the case, when large quantities of soil are removed and replaced, leading to major transformation of soil properties which may be un-related to pedogenic processes.

Keywords: adaptation, shrink-swell, sealing, SUDS, heat island, policy

Introduction

Urban soils are typically more varied and complex than rural soils, fulfilling a wide range of functions and services. In 2010, 51% of the global population lived in urban areas; this is projected to rise to 70% by 2050 (Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, 2011) so the global soil resource subject to urbanisation and demographic change is likely to increase substantially over the coming decades. As with rural soils, urban soils are very likely to be subject to more extreme variations in climate over the coming decades (IPCC, 2007). This will influence their fundamental properties and the functions they fulfil. There is a need to understand the potential impacts of climate change on urban soils to ensure that the services and natural capital they currently provide are not lost or degraded, and the functions they fulfil can be protected or enhanced.

In this review we consider urban soils to include any soil of natural or anthropogenic origin (e.g. made ground, including engineered fill) or soil that has been modified, for example by the removal of topsoil or its mixture with the subsoil. Urban soils exhibit large variations over short lateral and vertical spatial scales (Simpson, 1996). In urban areas, soils which deliver very different functions can occur within short-distances of one another. These soils include those with intact profiles, soils deposited by man with no distinct horizons and soils with sealed surfaces. These urban soils can be classified as either Technosols or Anthrosols (IUSS Working Group WRB, 2006). Both classes of soil are significantly affected by human activity however, in the case of Technosols there is little evidence of the long term pedogenetic change associated with Anthrosols. Technosols are typically the dominant soil classification in urban environments. Their composition is dominated by anthropogenic artefacts, with properties substantially different from those of natural soil materials and such soils have often lost their natural pedogenetic horizons.

Urban soils are subject to unique, and sometimes intense, environmental pressures not found in rural areas. For example, in some parts of the world they have been subject to substantially greater pollution (Marchant *et al.*, 2011), mixing and compaction (Jim, 1998) compared to non-urban soils which influences soil microbial processes and habitats. The net result is that urban soils have substantively different properties and functions in comparison to the soils of less disturbed, rural landscapes. Compared to rural soils, research into the services urban soils provide has been limited. For example, to our knowledge no research has been published to date on organic matter turnover in urban soils, although comparisons have been made between the quantities and types of organic carbon across transitions between urban and rural land use (Pouyat *et al.*, 2002; Rawlins *et al.*, 2008). Studies have shown that basal rates of respiration in urban soils are commonly elevated in comparison to rural equivalents (Post & Beeby, 1996). The implication of these findings on the role of urban soils in the global carbon cycle, and on the soils capacity to sequester atmospheric CO_2 remains unclear.

A substantial proportion of urban land comprises sealed surfaces where, with the exception of providing support for construction and development, soils deliver a limited range of functions as a consequence of being sealed. It has been estimated that up to 40% of the urban area of Cambridge (UK) comprised sealed surfaces (Wood *et al.*, 2006); the average proportion estimated for urban areas of Germany is slightly larger (52%; European Environment Agency (2002). Widespread sealing of urban surfaces reduces the capacity of soils to infiltrate surface water and increases the proportion of runoff which increases the likelihood of surface water, pluvial flooding (Woods-Ballard *et al.*, 2007; Defra, 2008). Typically, sealed surfaces have a lower albedo and absorb more solar radiation because they are darker or less reflective than soil and its associated vegetation. An increased proportion of sealed surfaces leads to a stronger urban heat island effect where local temperatures are typically a few degrees higher than surrounding rural land (Yuan & Bauer, 2007). Also, any change in the proportion of soil and vegetation cover resulting from climate change could have a significant impact on the magnitude and intensity of the urban heat island effect.

Soil management and the evolution of soil properties in urban areas are influenced by the interaction of humans and the subsurface; rapid transformation cycles are imposed upon these soils compared with undisturbed areas. The two dominant factors which determine soil management practices are: i) the policies and practices associated with development and construction under various planning regimes and, ii) management practices adopted by numerous small and medium-sized private and public landowners. This has implications for any coordinated policy measures designed to enhance soil functions across urban landscapes.

Projected climate change will have both direct and indirect effects on soil properties and processes; both require consideration when evaluating impacts on soil functions. Direct impacts include variations in soil moisture due to variations in precipitation, evapotranspiration and erosion. Examples of indirect effects of climate change are increasing average temperatures, and a longer growing season that will enhance net primary productivity, increasing litter inputs to soil and the turnover of organic carbon, leading to changes in urban soil biota.

The aim of this review is to provide an inventory of urban soil functions and their associated climate impacts. We then use urban soil functions across England as an exemplar to highlight those which are most likely to be significantly impacted by projected changes in climate. We provide an assessment of adaptation measures which could help to ameliorate these potential climate change impacts on urban soil functions and potential developments in urban soil policy.

An inventory of urban soil functions

An inventory of urban soil functions, based on the typology of the Millennium Ecosystem Assessment (MEA; Alcamo *et al*., 2003) is presented in Table 1. In addition to the ecosystem services-based categories specified by the framework of the MEA we include 'carrying' as a soil function because we consider it plays an important role in the services provided by urban soils. Each of the main functions or types of service is discussed below in more detail.

Supporting

The supporting soil functions in urban areas are generally of low provision in relation to other soil systems. It has been suggested that urban soils have a distinct biogeochemistry (Kaye *et al.*, 2006), which have major effects on ecosystem function (Alberti, 2005), with consequences for resilience of these systems, such that they are susceptible to threshold effects leading to collapse of function (Alberti & Marzaluff, 2004). Appropriation of net primary productivity (NPP) by human society has been explored for flows of carbon into food, fibre and energy on a global scale (Imhoff *et al.*, 2004), but little work has been carried out on the loss of NPP as a result of urbanisation. For example a recent report by (Deyong *et al.*, 2009) demonstrated that urbanization of Shenzhen City, China, has irreversibly transformed about 20.2% of Shenzhen's surface area between 1999-2005. Loss of NPP totalled 321 gigagrams (Gg) of carbon (C), an average annual reduction of 45.9 Gg C. For every square km of Shenzhen City, NPP was on average reduced by 0.0017 Gg C during 1999-2005. The loss of NPP is equivalent to a reduction in absorption of 142 Gg CO_2e (carbon dioxide equivalent) and release of 105 Gg CO_2e (carbon dioxide equivalent). Urban areas have predominantly developed in areas of high biodiversity (O'Neill & Abson, 2009), and loss in NPP has knock-on effects through loss of biodiversity (Haberl *et al.*, 2005). Soil formation through weathering is restricted by disruption to natural hydrology (sealing). Nutrient cycling and primary production are disrupted by the patchiness of the occurrence of suitable unsealed soils. The rising cost of food and the movement towards consumption of locally produced food from domestic gardens (Hopkins, 2008) which typically account for

22-27% of land in urban areas on the UK (Loram *et al.*, 2007) could substantially enhance primary production and associated nutrient cycling in urban soils.

Provisioning

The provisioning functions of urban soils are generally of a lower status when compared to other soil systems; the patchiness and sealed nature of much urban soil provides a limited amount of food, water, wood and fibre, and fuel per unit area, outside of allotments and back-garden plots. The storage of organic carbon in urban soil may be enhanced relative to equivalent rural soil due to either differences in land management practices or local addition of recalcitrant black carbon (Rawlins *et al.*, 2008). Carbon storage in urban soil could be enhanced by the application of fine demolition wastes to soil leading to the formation of inorganic carbonate (Manning, 2008). Anthropogenic wastes such as concrete and gypsum ($CaSO_4$) from plaster and plasterboard are frequently found in Technosols. Data from the British Geological Survey (unpublished) show that Ca concentrations in urban soils of England are greater than their rural equivalents over the same parent material types. Calculations based on the excess quantities of soil Ca based on data from geochemical analyses of soils from urban and rural areas suggest that urban soils in South East England have the capacity to sequester 0.5 Mt C (5×10^{-04} Gt C) in the form of inorganic carbon (Whitmore, pers. comm.).

Regulating

The regulating function of urban soils which may be most severely impacted by climate change relate to runoff and flooding. A large proportion of urban soil surfaces are sealed, severing the pathway between the soil surface and groundwater, and removing the soils contribution to flow regulation and water storage, leading to increases in run-off quantity

(Wessolek & Facklam, 1997; Praskievicz & Chang, 2009; Jacobson, 2011). During construction, topsoil material is often removed and stockpiled either for future reuse on site or transported off-site as a resource to be used in other development activities. Construction processes including removal of material using mechanical excavators, increase the susceptibility of soil to sealing through compaction (Harris *et al.*, 1989). Loss of soil function through sealing also occurs through addition of anthropogenic material used for paving and roads. Sealing causes loss of soil function as it introduces a physical barrier between soils and the atmosphere, reducing their capacity to exchange air and water (Wood *et al.*, 2005). Compaction (over-compaction) of soil by heavy machinery can lead to reduction in infiltration rates and enhanced local erosion of soil by water (e.g. Wang *et al.,* 2008). However, a recent study from the city of Leicester (England) suggests that on average urban soils are not compacted in relation to rural equivalents (Edmondson *et al.,* 2011)

Little is clearly understood concerning the role of soils in disease regulation due to the exposure of human populations to microbial ecology and genotoxic hazards. Soils are known to be capable of supporting aetiological (disease causing) agents (Oyeka & Okoli, 2002; White & Claxton, 2004). Increased average soil temperatures could increase survival rates of some organisms and so represent an increased risk to public health as the soil becomes less efficient at regulating soil borne aetiological agents. These risks are likely to be transient because of low survival rates of *ex vivo* pathogens within the soil, however survival will vary from pathogen to pathogen and precise environmental conditions (Santamaria and Toranzos, 2003) and enteric viruses have proven to be quite resilient (Rzezutka and Cook, 2004) .

Carrying

Although not included in the Millennium Ecosystem Assessment typology (which was based on ecosystem services), urban soils fulfil a range of carrying functions. They carry, with associated fill material, a complex range of piped utilities (e.g. water, electric, gas) and structures. Due to differences in construction practices both within and between countries, it is difficult to make general statements concerning the impacts of climate change and its influence on the role of soil in carrying structures. The foundations of buildings in urban areas of developed nations are typically constructed in the soil parent material (including superficial deposits) or bedrock. However, there are considerable problems associated with foundations built on expansive subsoil (Chen, 1988). These are prone to disturbance through natural processes, corrosion associated with chemical properties and disruption due to soil movement. There is considerable potential for disruption to the carrier functions of soil due to soil movement, specifically shrink and swell associated with certain clays minerals (Low, 1980). Urban soils also carry electrical earthing structures. All electrical transmission equipment requires some form of earthing (also termed grounding) to maintain continuity and safety of supply. Earthing is often achieved by driving steel and copper rods into the soil and geological foundations of the equipment being earthed (British Standards Institution, 2011). Earthing potential is principally controlled by its moisture content; lower moisture contents provide smaller earthing potentials.

Cultural

The cultural benefits of vegetated urban green space, which rely on soils for their biogeochemical cycling, were recently demonstrated from a study in England; it showed that populations exposed to the greenest environments also have lowest levels of health inequality related to income deprivation (Mitchell & Popham, 2008). Isolated and individual urban green spaces often also represent considerable cultural heritage (ancient parks and gardens) or are in the form of contemporary sporting venues. Sports facilities form some of the largest green spaces within the urban environment, helping to mitigate the urban heat-island effect and allowing water infiltration through their unsealed surface.

Assessment of climate change impacts on urban soil functions across England

The impacts of climate change on urban soil functions across the globe will vary according to the magnitude and direction of changes in local or regional climates, and the nature and properties of local soil types in urban areas. In this study we used the urban soils of England – which in 2007 comprised around 9.0% of the land surface (Morton et al., 2011) – as an exemplar. A broader assessment of all ecosystem services provided in urban areas of the UK was recently undertaken as part of the UK National Ecosystem Assessment (Davies *et al*., 2011); our focus here is on soil functions in particular and the impacts of climate change upon them. A summary of the main factors of soil formation across England are provided by Avery (1990). We focus on those functions where the magnitude of the impacts of projected climate change on soil function across England are likely to be moderate or large (Table 1). In Table 1 we have designated each function into one of three classes (small, moderate or large) for each of three categories (current state, potential for enhancement and potential impacts of climate drivers on soil functions) based on our knowledge, with our reasoning summarised below.

To make assessments of the likely impacts of climate change we have used summary outputs from the UK Climate Change Projections 2009 (Murphy *et al.*, 2009) on mean changes in seasonal (winter and summer) temperature, rainfall and annual rainfall. Our assessment is based on a mid-range projection (2040-2069) using the medium emission scenario, plus the most likely outcome (50% probability level). Further details on the scientific basis of the climate projections are provided by Murphy *et al.* (2009).

Support for development and carrying utilities

Subsoil provides support for building foundations and buried utility services (e.g. electric, water, gas etc.). Where the subsoil comprises a substantial (>30%) proportion of expansible clay minerals, inherited from the geological parent material, the clays within these soils can prove to be a significant hazard to engineering construction due to their ability to shrink and swell. This occurs as a result of larger seasonal changes in soil moisture content (projected to be greater in England as a result of more extreme dry and wet weather), local changes such as leakage from water supply pipes or drains, or following either the planting, severe pruning or removal of trees. In the UK, the shrinkage and swelling of clay soils is the single most common cause of foundation movements which damage domestic buildings (Crilly & Chapman, 1999). They cause damage to dwellings and buried services which can be expensive to remedy, typically £10k per property (Doornkamp, 1993). The factors which determine spatial and temporal variations in the magnitudes of shrink-swell include:

i) subsoil properties (amount and type of clay minerals)
ii) climate variables (temperature, rainfall and solar radiation) leading to changes in soil moisture
iii) uptake of water by roots (particularly trees) leading to changes in soil moisture

Where deep cracks form due to prolonged dry periods, particulate debris can enter them preventing full closure and water can penetrate more deeply into the soil, thus enhancing swelling. In 1991, after the preceding drought, claims peaked at over £500 million (Association of British Insurers, 2004). The Association of British Insurers has predicted that by 2050 the annual average cost of subsidence claims could increase from £300 million to £600 million with an extreme or ‘event’ year costing £1,200 million (Association of British

Insurers, 2004). In a study of subsidence claims related to shrink–swell clays, soils developed over the London Clay have been described as ‘the most commonly encountered, problematic soil [type]’ (Crilly, 2001) with some London Boroughs proving more problematic than others.

Most of the clay-rich soils and those which pose the greatest shrink–swell hazard are located in the south east of England. Figure 1 shows the distribution of susceptible parent material types across England. The areas highlighted are dominated by 'clay' formations which are too young to have been changed into stronger 'mudrocks', so they absorb and lose moisture. Clay-bearing mudrocks elsewhere in the country are older and have been hardened by burial deep in the earth, and are less expansible. Some superficial deposits – such as alluvium, peat and laminated clays – can also be susceptible to soil subsidence and heave. Some of the urban areas affected by shrink–swell clays are London (15% of the UK population, 75% of the total area affected), and several other major towns and cities across England shown in Figure 1.

Much of the historical water mains network in the UK is commonly constructed from cast iron although some has been replaced by modern materials including high density polyethylene (Schmidt et al, 2006). In the former, corrosion and mechanical failure of utilities may occur as a result of the chemical and mechanical interaction between soils and the utility buried in the ground, especially where utilities have been installed using trench excavation and non-granular fills from surrounding soils. Volume changes in soils as a result of variations in soil moisture content, may cause ground movement surrounding utilities and cause failure and breakage. For example, Hu and Humble (2007) identify volume change in montmorillonite [clay] rich deposits as one of the contributing factors to failure of asbestos cement water mains in Regina (Saskatchewan, Canada). Mechanical failure of cast iron water mains due to within soil volume change of clay-rich materials of the London Clay Formation has been observed and often related to periods of intense wetting from rainfall (Schmidt et al, 2006).

As demonstrated in a recent study, the substantial projected changes in the seasonal distribution of rainfall for England– wetter winters and drier summers – are likely to lead to increased shrink-swell behaviour and corresponding ground movement in soils over the clay-rich lithologies in southern and eastern England (Harrison *et al.,* 2012). This is where property development has been most concentrated and substantial expenditure may be required to repair dwellings. Damage to structures due to shrink-swell of clay-rich soil has serious financial implications for loss of urban soil function due to projected climate change across England.

Carbon storage and primary production

It is important to consider climate change impacts on the storage of both organic and inorganic carbon in urban soil, although as with rural soils (Rawlins *et al.*, 2011) it is likely that the former is substantially larger across most urban centres compared to the latter. It is not clear how the increase in mean annual temperatures and its interaction with the likely greater range of soil moisture – due to increased differences in seasonal precipitation (Murphy *et al.*, 2009) – will influence below ground organic matter turnover, and the quantity of carbon stored in the soil. Greater mean annual temperatures will lead to an increase in primary productivity and larger organic carbon inputs to the soil. By contrast, prolonged dry summers in Europe will lead to reductions in primary productivity – unless counteracted by urban irrigation – and smaller C inputs to the soil (Ciais *et al.*, 2005). These changes in climate are also likely to lead to changes in the proportions of the dominant plant species in urban areas which will influence above and below ground partitioning of organic carbon.

The combination of seasonal effects and the changes in plant species and soil biota will determine the overall effect on soil organic carbon. The broad national scale climate trends are likely to have substantially greater impacts on soil carbon than those at regional scale, but will also depend on local soil properties and cultivation practices. Considering the large number of factors which will determine overall changes in organic carbon storage in urban soils it is not possible to draw conclusions on either the direction or magnitude of future change in their storage of organic carbon.

Storage of inorganic carbon (as calcium carbonate) may be enhanced in urban soil because of the greater concentrations of calcium observed due to the dispersal of construction wastes including hydrated cement minerals, the mineral portlandite ($Ca(OH)_2$) and perhaps to a lesser extent, plasterboard wastes (gypsum; $CaSO_4$). This excess Ca^{2+} when leached into the subsoil forms inorganic carbon by combining with carbonate ions derived from the organic acids released by plant roots. There is an inverse relationship between depth of carbonate formation and mean annual rainfall (Jenny, 1980); as this reduces from 700 towards 500 mm per annum, carbonate formation moves from depths of around 750 mm to 500 mm in the soil profile. Changes in mean annual rainfall will lead to changes in the depth and quantity of carbonate formation. The overall trend in mean annual rainfall is relatively stable across England (Murphy *et al.*, 2009) so based on these projections the quantity of inorganic carbon stored in urban soil is unlikely to change substantially. Without intervention, changes to the quantities of inorganic carbon stored in urban soils from projected climate change are likely to be limited.

Carry earthing

To achieve appropriate earthing to the standard of 10 Ohms resistance (at the earth) for 11 kV substations - which are common across England - a series of copper rods are inserted into soil and superficial or bedrock deposits (Energy Networks Association, 2003). The resistance of the earth path is influenced by the resistivity of the soil and geology surrounding the earth rod; which is a function of the moisture and clay content of the material, as well as the ground temperature. Resistivity values increase by several orders of magnitude (i.e. poorer earthing) as soil moisture declines and by a few percent as temperature increases across the range observed in the temperate climate of England. The projected reduction in mean summer precipitation (Murphy *et al.*, 2009) will lead to greater soil moisture deficits in summer and those sub-stations with coarse textured soils and associated free-draining hydrogeological conditions will be prone to a failed or failing earthing specification (providing insufficient earthing and unsafe power transmittance). The scope of this effect could be assessed using coupled soil moisture and groundwater models. The greatest problems are likely to occur in the driest periods of the year (typically July - September in England) depending on summer weather. We anticipate that long, dry summer periods could inhibit the role of soil and underlying parent materials to provide sufficient earthing at substations.

Regulation of water quantity

When considering the impact of climate change on the role of soils in regulating floods, it is important to distinguish between flash floods – extreme localised rain that may cause runoff from unsaturated soil – and floods caused by runoff from largely saturated soils through heavy rain over prolonged periods. In the case of the former, prolonged periods of dry weather during summer months is known to increase soil hydrophobicity (Doerr *et al.*, 2000) which may enhance rapid runoff in urbanised catchments. Although sandy soils with larger infiltration capacities are considered to be more prone to hydrophobicity, it has been observed in soils with clay contents of up to 40% (Dekker & Ritsema, 1996). There are knowledge gaps concerning the precise mechanisms which result in soils becoming hydrophobic and its spatial variability can be substantial. Given the large proportion of sealed ground observed in all urban areas, any increase in runoff caused by changes to the hydrological properties of urban soil – caused by increased hydrophobicity – could have significant consequences for the magnitude of flooding in urban areas. Annual costs across England and Wales are currently around £270 million (Parliamentary Office of Science and Technology, 2007). Assessing the magnitude of this effect will be difficult; it is necessary to identify the organic compounds and biological processes which confer hydrophobic properties on soil. This will be particularly challenging in urban areas where dominant plant species and litter derived from them change over short distances. When considering floods associated with prolonged periods of rain it is necessary to consider the impacts of climate change on soil structural and hydraulic properties. The greater variations in soil moisture resulting from large changes in mean seasonal rainfall may alter soil structural hydraulic properties. However, changes in soil structure will also depend on the quantity and distribution of soil organic matter that is a function of both climate drivers and land management practice. Given the range of factors which will influence soil hydraulic properties, it is not possible to make definitive statements concerning the impact of anticipated climate change on the role of urban soils in regulation of floods associated with prolonged rainfall.

Soil biology

As with natural soil systems the microbial community dynamics of urban soils are closely related to nutrient availability within the soil (Beyer *et al.*, 1995). The soil organic matter has a key functional role for urban soils as both a nutrient reserve but also in a buffering capacity to contaminants (Craul, 1985). Anthropogenic influences on the urban soil environment therefore have a substantial effect on soil flora and fauna, but the implications of climate change are likely to be the same as for the soil systems of natural environments. The understanding of relationships between soil chemistry, physical properties and the microbial habitat functions of urban soils is slowly being addressed to enable quantification of the provision of ecosystem goods and services in urban environments (Lorenz *et al.*, 2006). Soil microbial communities are clearly different in the urban setting, compared to those found in rural ones, but it is not clear how these differences are functionally manifested. Research more commonly investigates the higher trophic levels, typically plants but sometimes soil animals (McDonnell *et al.*, 1997; Lorenz *et al.*, 2006; Cheng *et al.*, 2008; Pieper & Weigmann, 2008). A study in Stuttgart (Germany), showed that the variability in the size of the urban soils microbial community ranged from approximately 1.5 g C kg^{-1} microbial biomass in parks and gardens to a factor of ten less in railway sidings (Lorenz & Kandeler, 2005). Research conducted in Aberdeen (UK) highlighted that while metal concentrations cause various responses in community dynamics, only the concentration of lead (Pb) was significantly negatively correlated with microbial biomass C (Yuangen *et al.*, 2006). This is of key importance because the residence time of Pb in urban soils has been reported to be large, as is the case in Hong Kong for example, despite the majority of engine fuels now not using Pb as an additive (Wong & Li, 2004).The use of platinum group elements in petrol car engine catalytic converters has also increased the concentration of these as pollutants in urban soils and increases in these metal ion concentrations also has a detectable effect on the structure of the microbial community (Beccaloni *et al.*, 2005). The current lack of data and understanding of the biological processes involved in the ecosystem goods and services which are delivered by urban soil systems means that assessing climate impacts on soil community diversity is not possible.

A thorough review on the mutagenic risks of the soil highlighted that the community dynamics in urban soils are almost completely unknown (White & Claxton, 2004). It is clear that the soil matrix is capable of supporting a range of aetiological agents (Oyeka & Okoli, 2002; Arnesen *et al.*, 2008). The risks are largely un-quantified, but are likely to be transient, because of the low *ex vivo* survival rates of pathogenic organisms. The high density of human activity in the vicinity of urban soils means that cellular debris from humans within the soil is likely to be considerably higher than in natural soils. Observations of aetiologically important micro-organisms are commonly recorded in urban soils in the subtropics and tropics where soil temperatures are closer to the pathogenic bacterial survival optimum (Zibilske & Weaver, 1978). As average soil temperatures increase in England the survival rates of pathogenic micro-organisms in the soil may increase. In a source-pathway-receptor model, this could present an increased problem as the pathway-receptor components of the aetiological risk already exists in the urban environment, although data is extremely limited in this area. Mechanisms that involve skin abrasions on the soil surface present a significant aetiological risk and are likely to be of greatest importance in sports facilities or children's play areas (Turbeville *et al.*, 2006). Geophagus or broken skin exposure to the microbial community within the soil that results in infection is perceived as relatively low, both because of the likely concentration of human pathogens in the soil, but also because of the routes of entry to the human body (Odds, 1991). Rate of ingestion of soil by children is relatively high, 95% of the population consume 208 milligrams per day (mg d^{-1}) or less, with a mean estimated intake of 45 mg d^{-1} or less (Stanek & Calabrese, 1995). The hazards associated with these soil borne pathogens range from extremely hazardous e.g. Typhoid fever

(*Salmonella typhi*) to relatively low e,g. *Bacillus cereus*, a form of food poisoning. Taking the case of *B. cereus*, which is normally a dormant soil microbe, its ability to cause infection, with symptoms such as diarrhoea and vomiting, are related to the virulence of the strain (Arnesen *et al.*, 2008). Where disease is caused by a highly virulent strains of *B. cereus* in an immuno-compromised individual the infection has been reported to be fatal (Mahler *et al.*, 1997; Dierick *et al.*, 2005). The result is an increased dominance of keratinophilic microbes, some of which consume the substrate in the soil matrix only, indicated by the heightened protease activity in the soil microbial community (Majer *et al.*, 2009).

Some fungi resident in the soil also remain pathogenic to humans (Oyeka & Okoli, 2002). Samples taken in Joao Pessos (Brazil) showed that large amounts of dermatophytes were present in soil samples taken around the city. The human specific fungal pathogen *Trichophyton tonsurans* (ring worm) was found in 3.8% of all dermatophytes that were isolated (Da Silva Pontes & Oliveira, 2008). A similar survey conducted in Barcelona (Spain) showed that 8% of the fungi isolated from soil samples taken throughout the city were *Microsporum gypseum* which is the aetiological agent in 22% of body ringworm cases and 2% of beard ringworm cases in Spain (Calvo *et al.*, 1984). Under climate change scenarios where there is a warming of soil temperatures these risks may increase in the urban soils of England. Only a small number of viable cells are required to cause infection. Survival rates for some *Salmonella* species can be as long as 42 days under ideal conditions (Zibilske & Weaver, 1978) and warmer conditions will enhance the ability of the soil to support viable *Cryptosporidium parvum* oocysts (Jenkins *et al.*, 1999; Walker & Redelman, 2004). Further research is required to determine the specific risk factors associated with urban soils in heavily populated areas.

Archaeological heritage

In many UK urban centres, soils provide an environmental matrix in which buried archaeological remains are preserved. They represent material deposited as a result of settlement, urbanisation and population growth from initial human occupation through to major industrial expansion and represent a finite, non-renewable heritage resource. Government Planning Policy Guidance (DCLG, 2006) favours physical preservation *in situ* of buried archaeological heritage. Archaeological remains in the subsurface are therefore susceptible to *in situ* deterioration as a result of climate change impacts. The degree to which they may deteriorate is dependent on their form (organic/inorganic) and the physical, chemical and biological properties of the environment in which they are buried (Holden *et al.*, 2006; Howard *et al.*, 2006). As such, direct climate change impacts and the societal responses to it, have the potential to alter the environmental conditions which determine the preservation or degradation of archaeological remains.

Direct impacts include changes to river system geomorphology in response to increased precipitation frequency and intensity (spatial fluctuations in erosion and increased sedimentation rates) and changes in groundwater levels and chemical properties (including pH, moisture content, and redox potential). Changes to seasonal precipitation may impact on subsurface groundwater levels, changing redox conditions and affecting preservation potential. Changes in groundwater levels may cause fluctuations between aerobic and anaerobic conditions leading to the formation of potentially corrosive chemical species (Holden *et al.*, 2006). The degree of waterlogging is dependent on many factors, including soil and subsoil type, topography and degree of surface sealing (Holden *et al.*, 2006). In general, elevated groundwater tables result in saturated (waterlogged) archaeological deposits and anaerobic conditions through loss of oxidising chemical species, enhancing preservation potential, especially for organic archaeological remains. In general, lowering of groundwater levels may promote oxidising conditions and an associated destruction in organic remains (Caple, 1996).

Assessment of adaptation measures

There have been numerous calls to change the way in which we plan, build, manage and maintain cities, and our way of life within them – this will be critical in our response to climate change (Dawson, 2007). It is also essential that the measures made to provide effective adaptation and mitigation be made in a holistic manner, to avoid the unintended, deleterious consequences of single issue interventions (Betts, 2007). Current proposed changes in the planning system for England may transform the way we manage land and the ecosystem services it delivers. Measures to adapt to environmental change through increased climate resilience - whilst meeting the needs of sustainable development - should protect and enhance the natural and historic environment and deliver economic growth and societal well-being. The UK government's National Planning Policy Framework (DCLG, 2011) and the Localism Bill aim to achieve this with transition from national spatial planning to greater community engagement and partnership working at the local level through the development of local neighbourhood plans. Such plans will aim to set strategic neighbourhood priorities, including those to adapt to climate change to protect the natural and historic environment in urban areas. Cities may well provide centres for developing mitigation and adaptation strategies with the potential for widespread adoption (Grimm *et al.*, 2008). Here we address the question of how urban soils and landscapes might be managed to adapt to changes in soil properties and functions caused by projected climate change. Adaptation measures need to be considered in the context of land management in urban environments which is more complex, undertaken on smaller spatial scales, and involves a greater number and range of stakeholders than the rural environment. It is important to recognise, however, that the impact of activities within urban areas spreads far beyond their physical footprint. Any measures which have the effect of shrinking the urban ‘ecological footprint’ will relieve pressures on rural areas.

Three types of adaptation measure can be distinguished:

a) local adaptations measure (short-term). For example, implementation of specific drainage measures, changes in construction practices
b) development of green architecture, increase in such practices as ‘vertical farming’
c) interventions through local and neighbourhood plans (longer-term), and long-term strategic planning, within the planning regime. For example, changes in the distribution and types of land use and infrastructure which influence the nature of soil function – and treating each development site as part of a connected system. This may require soil data at a far higher resolution across England than has, hitherto, been available.

We limit our assessment to adaptation measures which influence those soil functions identified above which are likely to have the most substantial impacts across England. A summary of local adaptation measures to address potential losses of soil function within the urban environment are shown in Table 2. Below we assess whether local adaptation measures are likely to overcome the losses of soil function associated with projected climate change based on the published literature and our expert knowledge. We also comment on how planning regimes could help to prevent loss of soil function.

Water storage and flood regulation

The projected increase in mean winter precipitation and the greater likelihood of more intense rainstorms will exacerbate the occurrence of flood events in urban areas due to the occurrence of a large proportion of sealed surfaces (Scalenghe & Marsan, 2009). Given the large number and small scale of local soil cultivation practices, we consider it is impractical to attempt to alter these to reduce rapid, urban-wide runoff. However, there are a range of measures which can reduce urban storm water runoff including the use of porous paving surfaces and green roofs as part of sustainable drainage systems (SUDS) design.

Well designed, managed and maintained SUDS systems have the potential to attenuate the impacts of increased surface water runoff (quantity and quality) as a result of soil function loss through surface sealing. SUDS have various functions and design criteria but all aim to achieve the key objectives of reducing overland runoff rates and volumes (surface water flooding), reducing pollutant concentrations in surface water, reducing discharges to combined sewer systems and enhancing biodiversity and amenity value. By attenuating the impacts of surface water flooding, SUDS also have the potential to reduce the possible impacts of increased soil erosion from higher intensity rainfall events. The main types of SUDS and their characteristics are described by Woods-Ballard *et al.* (2007) and include filter strips, swales, infiltration basins, wetponds, extended detention basins, constructed wetlands, filter drains, pervious surfaces and green roofs.

SUDS can mitigate the impacts of excess surface water flows, volumes and quality through introducing three key intervention processes; infiltration, detention/attenuation and conveyance (Woods-Ballard *et al.*, 2007). All SUDS, if used to mitigate the impact of loss of soil function, should aim initially to prevent runoff. If this is not practicable, a hierarchy of mitigation measures may be used to progress from source control, to site control to regional control.

Measures for enhancing water infiltration using porous paving materials could significantly increase water storage under sealed surfaces which are currently impervious, or where paving is used in future development. Experiments have shown that runoff coefficients -where a value of one equates to runoff of all incident precipitation - for some porous paving materials are close to zero (Hou *et al.*, 2008) but can be as large as 0.70 compared with values of between 0.73 and 0.97 for more impervious materials (Ferguson, 2005). A larger scale study in the City of Yokohama (Japan) has shown that in areas where porous paving surfaces are used in conjunction with infiltration pipes, peak runoff was reduced by 15 - 20% (Watanabe, 1995). Identification of urban areas most prone to enhanced storm runoff using catchment-based hydrological modelling (Praskievicz & Chang, 2009) would provide a cost-effective means for targeted replacement of impervious with pervious paving. A case study from the UK has demonstrated that hydrological models can be modified to account for urbanization (Kjeldsen, 2009). Catchment-scale hydrological modelling could help to identify urban catchments prone to flash flooding. This would highlight where local planning controls are required to limit increases in the proportion of sealed surfaces. This could form part of a wider, web-based system for local planners assessing the risks associated with surface sealing and increased runoff.

A modelling approach has been used to identify areas of urban catchments where installation of green roofs could significantly reduce storm runoff for smaller events (Carter & Jackson, 2007). Application of data on annual water retention for a region of Brussels (Belgium) has suggested that green roofing of 10% of all buildings would result in a runoff reduction of 2.7% (Mentens *et al.*, 2006).

Support for construction and earthing

There is no simple adaptation measure for existing structures which may be prone to ground subsidence associated with shrink-swell behaviour. Previous studies have shown that vegetation, and in particular trees close to dwellings, have a major impact on soil moisture regimes and subsidence. Driscoll (1983) presented a hierarchy of the potentially most damaging species and studied soil moisture regimes associated with tree roots using electrical resistivity imaging (ERI) under oak and willow. More recently, the same methods were applied at sites with the same species demonstrating that ERI may be an affordable, tree-induced subsidence assessment tool (Jones *et al.*, 2009). One potential approach is to combine geographic information to identify urban areas with expansible clay parent material types and sizeable trees which are sufficiently close to properties initiate subsidence. Geophysical ERI techniques could be applied to assess the level of risk, and site-specific intervention measures implemented, such as tree size reduction, or tree removal. It may be possible to alter soil moisture regimes by changing the nature of impervious surfaces close to properties. New-build construction should adopt foundation designs which avoid damage associated with shrink-swell induced subsidence under the likely greater fluctuations in soil moisture associated with projected climate change (Ross *et al*., 2007).

Soil and health – direct effects

Young children are at greatest risk of exposure (Nwachuku & Gerba, 2004) to pathogenic soil bacteria which may survive for longer periods as soil temperatures increase under projected climate change. The main adaptation measure is improved education of parents and young children on the need to minimise hand-to-mouth activity, the main exposure route to soil pathogens. Laboratory-based research is needed to quantify the magnitude of enhanced risks posed by pathogenic soil bacteria associated with their enhanced survival under warmer soil conditions. Traditional mechanisms such as media campaigns could be used to improve the public understanding of health threats associated with soil bacteria, particularly during the warmer, summer months. The impact of climate change on the range of foods available to grow in urban areas could have important health implications (Johns & Eyzaguirre, 2006).

Soil and health – indirect effects of enhanced biodiversity

It has been known for some time that diverse assemblages of vertebrates can dilute the impact of disease reservoir and vector organisms, by providing a wider range of food organisms, and direct predation control of vector organisms (Ostfeld & Keesing, 2000). Loss of biodiversity has been linked to an increase in the incidence of zoonotic diseases (Ostfeld, 2008). It would appear to follow that increasing the availability and diversity of terrestrial habitat available within urban areas may mitigate the predicted rise in disease as a result of climate change. There is also evidence that being exposed to key triggers, such as apprehension of butterflies and birds in an urban context, provides psychological cues enhancing mental well being, in addition to the opportunities for exercise offered by green spaces (Dustin *et al.*, 2010). Enhancement of biodiversity in these spaces, and their expansion, may lead to increased psychological benefit.

Preservation of archaeological heritage

Adaptation measures which might be considered to enhance the preservation of buried archaeology will always need to be assessed on a site-specific basis. The most likely adaptation is the requirement to reduce the fluctuation in local water tables and associated soil-moisture regimes which may increase due to changes in seasonal rainfall. Implementation of such adaptation measures would need to be consistent with any published guidance on archaeology and planning (DCLG, 2006; DCLG, 2011).

Biodiversity

Any sustained changes in climate will alter the range of habitats and species which survive and this may well be exaggerated in urban areas due to, *inter alia*, heat island effects. Some attempts have been made to model what kind of tree species might survive in a changed climate (Roloff *et al.*, 2009) – however these studies usually do not include soil functions and parameters in the models employed. As city gardens tend to contain collections of the world's flora, the most adapted species are likely to self-select (Kendal *et al*., 2012). However, there is a danger that these will also become invasive species, overrunning less aggressive species and compromising ecosystems function and structure. Soil biodiversity research in this area has tended to 'piggy-back' on studies of the impacts of climate change on plant species and communities – and none of these are specific to urban areas (Pickett et al, 2011).

Local planning regimes

There is a need to take an holistic, whole-systems approach to urban areas – they must be treated as ecosystems within larger drainage catchments as an agent of adaptation and mitigation (Biesbroek *et al.*, 2009). The planning system in England currently ignores ecosystem elements, and is largely driven by transport, economic, and demographic models. Current proposals for planning reform aim to transform this approach and include provision from protection and enhancement of the natural environment (DCLG, 2011). It is essential that, if we are to secure and enhance ecosystem service provision, that all natural capital assets are properly accounted for and evaluated, ideally using methodologies such as Defra's Ecosystem Approach (Defra, 2007), as a minimum requirement for all (re)-development proposals. With the advent of the new Localism Bill in England, it will be essential for Local Planning Officers to have access to high quality soils data at a resolution sufficient to make decisions within individual land holdings if ecosystem services are to be secured, in the face of both land conversion and climate change (Hindmarch *et al.*, 2006). Currently there is a lack of understanding and experience of ecosystem structure and function in planning departments in part due to the lack of tools suitable to support 'ecosystem goods and services' based approaches to planning. The intensification or consolidation as a planning policy tool for urban areas is one approach by which more efficient use of land could enhance soil functions, by limiting surface sealing for example, but there are potential pitfalls in its implementation (Williams, 1999).

Generic implications and policies relating to urban soil

Although we have used England as an exemplar, it is possible to draw some general conclusions from our synthesis relating to climate change impacts on urban soils in a broader context. Any assessment of such impacts requires some fundamental knowledge of the variation in soil types (and preferably their properties) across an urban area. Traditional soil survey maps are unlikely to be available for urban centres, so it may be necessary to rely on some combination of maps relating to bedrock (or Quaternary deposits) and widely available digital elevation/landform data (Farr *et al.*, 2007) with which soil types are often closely associated – linked to high resolution remote sensing to reveal extent of soil sealing – without some degree of permeability there is little prospect of delivering ecosystem services (Wood *et al.*, 2006). Such data would be necessary to make preliminary assessments on the likely distribution of the impacts of climate change on soil functions of the kind we presented for

England. It would also be necessary to have an understanding of the age and form of buried infrastructure in the urban area; for example, ageing and corrodible buried services may respond quite differently to climate-related impacts compared to recently installed, non-corrodible structures. The availability of this information often depends on the extent to which it is recorded and maintained. For many urban soil functions, our knowledge of the soil processes (e.g. organic matter turnover, biodiversity) governing them is still insufficient for us to be confident in making predictions relating to the direction of any change (Kaye *et al.*, 2006).

In England (as in many countries), there are few if any specific government policies relating to preserving or evaluating urban soil functions and their change over time. We can consider various components of the policy cycle which includes: (i) defining an issue, (ii) developing and implementing options, (iii) monitoring, and (iv) evaluation. One of the few examples where consideration has been given to urban soils across Europe relates to soil sealing, also referred to as land take. The European Commission recognises the importance of soil sealing and has begun to monitor it across member states (European Environment Agency, 2011). Such data is readily available by remote sensing which may in part account for why it is one of the first urban-related soil monitoring activities to be widely undertaken.

With the exception of soil sealing, there is currently no monitoring of soil or soil indicators in England which can be used to evaluate changes in urban soil functions (Defra, 2009). This is despite more recent recognition of the need to protect and develop natural capital such as urban soil (HM Government, 2011). Without an evidence base, trends in soil properties and functions cannot be detected. One of the challenges of soil monitoring in urban settings is the rapid changes which may be observed associated with large-scale interventions associated with development. For example, topsoil at a monitoring location may be completely removed and replaced leading to changes which cannot be related to natural processes or soil management activities. As an alternative, it may be possible to monitor the economic impacts associated with the loss of urban soil functions; for example, recording the number and costs of floods associated with urban storm runoff. However, it may not be possible to distinguish between the impacts of soil sealing and the increased frequency of intense rainfall events predicted by global climate models. The evaluation of urban soil functions and the development of monitoring activities and policies to address any loss is a topic which deserves greater attention at the start of the 21st century when urbanisation continues rapidly in most countries (United Nations, 2012).

Conclusions

1. Urban soils often have substantially different properties and functions compared to their rural equivalents.
2. There are likely to be both direct and indirect effects of climate change on soil urban functions. The former include shrink-swell associated ground movements causing damage to property, whilst the latter relate to the effects of temperature on the turnover of soil organic matter which will influence soil structure and infiltration rates.
3. Land management – which is undertaken at small scales in urban areas - will make it difficult to implement coordinated soil management practices making adaptation more challenging.
4. As urbanisation continues through the 21st century, governments urgently need to consider how best to monitor urban soils and their functions.

5. In England, the largest economic impacts of climate change on soil function is likely to be damage to property from ground movement associated with increased shrink-swell of clay-rich subsoil due to wider variations in soil moisture.
6. The large proportion of sealed surfaces in urban areas of developed nations will lead to greater problems associated with more extreme rainfall events, but there are many adaptation measures which can be implemented to mitigate these risks.

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List of Figure Captions

Figure 1 – The location of large urban areas across much of England in relation to soil parent material classified according to their degree of shrink-swell behaviour: low=white, pale grey = moderate, grey=high. Modified from Harrison *et al.*, (2009). Parts of northern and western England were not included in the map coverage because the majority of the shrink-swell prone soils occur in the south and east.

Table 1 – Urban soil services based on an extension to the Millennium Ecosystem Assessment typology and an assessment of some of their features related to projected climate change for England

Service	Examples	Current provision in comparison to undisturbed systems	Magnitude of potential for enhancement	Magnitude of potential impact* of climate drivers
Supporting	Soil formation	Small	Small	Small
	Nutrient cycling	Small	Moderate	Small
	Primary Production	Small	Moderate	Moderate
	Habitat space	Small	Small	Small
Provisioning	Food	Small	Moderate	Small
	Fresh water	Small	Small	Small
	Wood and fibre	Small	Small	Small
	Fuel	Small	Small	Small
	Carbon store/regulation	Small	Moderate	Small
Regulating	Climate/Temperature	Small	Small	Moderate
	Flood	Small	Large	Large
	Disease	Small		Large
	Water (attenuation of quantity)	Small	Small	Moderate
**Carrying	Carry structures	Large	Small	Large
	Electrical earthing	Large	Small	Large
Cultural	Aesthetic	Moderate	Moderate	Small
	Spiritual	Moderate	Moderate	Small
	Educational	Moderate	Moderate	Small
	Recreational	Large	Moderate	Small
	Archaeological	Moderate	Small	Large

* the magnitude of potential impacts are based on our knowledge of direct economic costs, or the likely costs to remedy damage, or mitigate loss of soil function (Defra, 2006)

**** our extension to the Millennium Ecosystem Assessment typology for soil-based services

Table 2 – Examples of local adaptation measures to address potential losses of soil function

Service	Loss of function	Scale	Intervention/Adaptation
Regulating	Flood, water storage Water quality Disease	All urban area Contaminated soils prone to flooding All urban area	Improve water holding capacity, SUDS* (inc green roofs and pervious surfaces) Source-pathway-receptor assessment / remediation Enhanced Biodiversity
Carrier	Ability to support construction and underpin utilities, electrical earthing	All urban area	Construction practices, tree removal / crown thinning.
Cultural	Loss of heritage and archaeology	Local / urban area specific	Specifically via the planning system and published guidance
Provisioning	Change in range of possible crops	Allotments/gardens	New varieties and practices

* Sustainable Drainage Systems

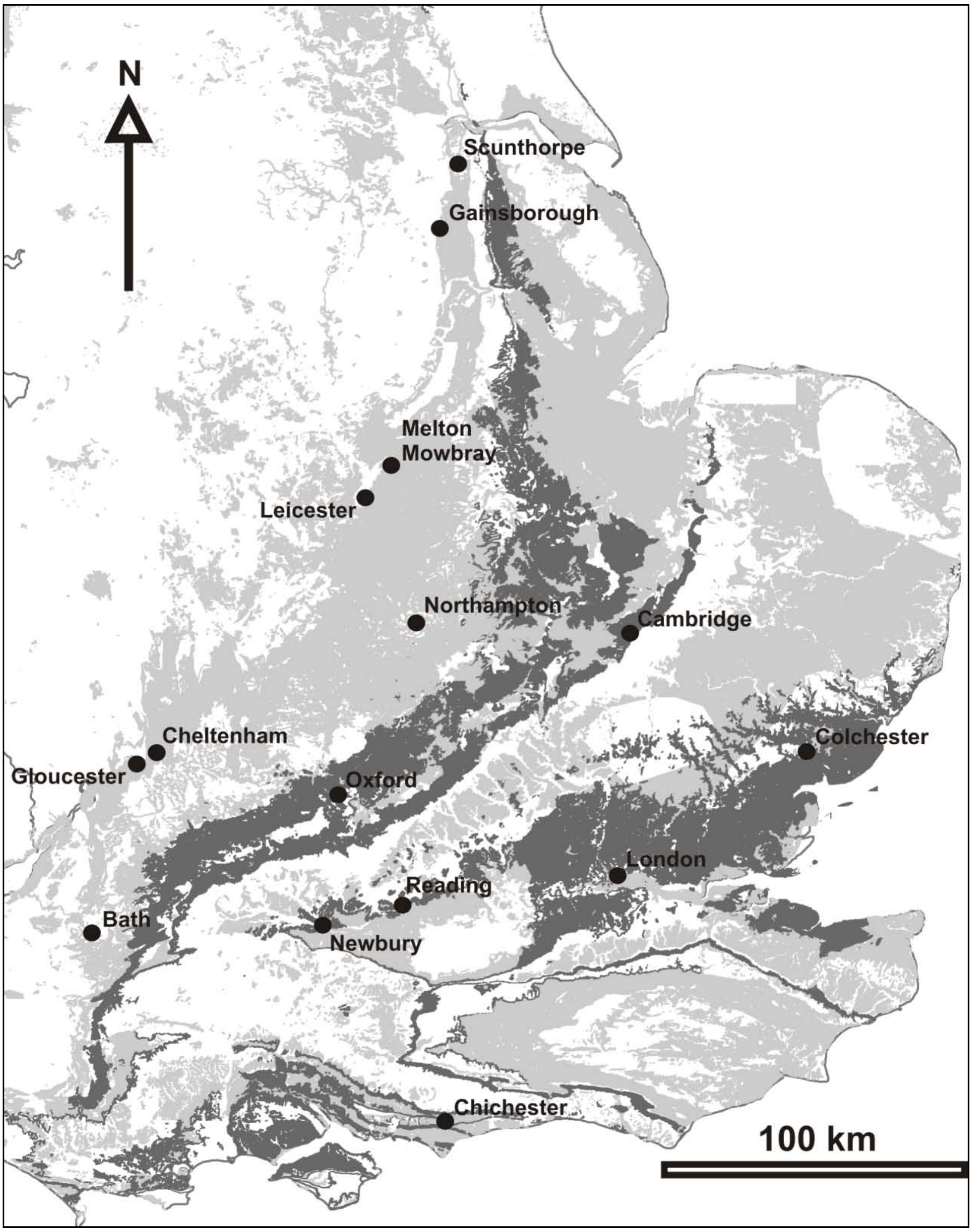
N
Scunthorpe
Gainsborough
Melton
Mowbray
Leicester
Northampton
Cambridge
Cheltenham
Gloucester
Oxford
Colchester
London
Reading
Bath
Newbury
Chichester
100 km

Figure 1