Designing a carbon capture function into urban soils

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Abstract

Soils, if designed and managed correctly, can retain carbon from the atmosphere as accumulated organic matter, refractory forms of carbon (e.g. biochar) or stable, inorganic, carbonate minerals. This soil 'carbon capture function' is highly applicable to the constructed environment in urban areas and should be considered when planning for new or existing developments. The total carbon capture potential of soils in cities may be as high as 7 Mt y^{-1} within the UK using biochar and accumulated carbonate minerals, which is equivalent in significance to other forms of geoengineering. Furthermore, soil and vegetation management practices may be implemented to accumulate plant-derived organic carbon in urban soils. The potential for substantial soil-based carbon sequestration in urban environments has yet to be realised, and the varied praxis of soil carbon capture presents accreditation and regulatory challenges to the planning system which need to be resolved.

1. Introduction

Human existence is wholly predicated on the services of soil and its resident organisms, through the storage and mobilisation of nutrients, turnover of carbon, retention of water and physical support for plant growth. These processes are basal components of large ecosystem services that are intrinsic to human survival.

Historically, the engineering community confined its interest in soil to understanding physical properties (geotechnics) and the mitigation of human health risk associated with contaminated land and water (environmental engineering). These disciplines are important when the objective is to develop suitable ground and foundations for structural stability, or the improvement of public health. However, they do not take into account the plethora of biogeochemical activity operating in soils that could be harnessed for human benefit.

Soil is the major terrestrial storage pool (1500 Gt C) in the global carbon cycle, being twice as large as the atmospheric pool (730 Gt C; Figure 1), and through which 120 Gt C returns to the atmosphere each year. The dominance of soil in this system has led to research in understanding its carbon sequestration potential (Lal, 2003), particularly concerning the manipulation of agricultural practices to accumulate organic carbon (0.6-1.2 Gt C y^{-1}). Importantly, as about 15% of atmospheric CO_2 passes through the coupled plant-soil system per year, this is an obvious system to manipulate for rapid removal of atmospheric CO_2 (Manning, 2008).

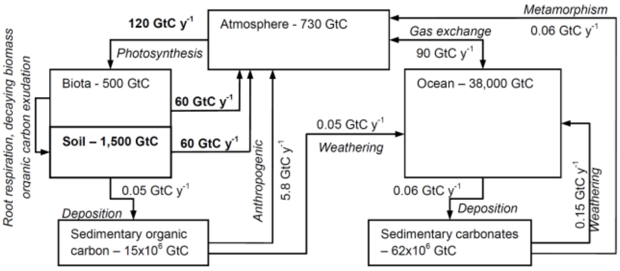

Figure 1: A simplified version of the global carbon cycle adapted from Dupre et al, (2003) and Rogner et al (2007).

The careful zoning of 'green' and 'blue' space in cities has been investigated for regulation of the urban heat island and to mitigate rapid runoff (Gill et al., 2007). Green and blue infrastructure uses the physical properties of vegetation, wetlands and soils for human benefit. The controlled accumulation of carbon in soil is similarly a green infrastructure that uses physical and biochemical processes for human benefit. Certainly, an engineer of the ecological age (Head, 2008) will be capable of designing ecosystem services into new developments. The aim of this paper is to present to the engineering community a vision of how soils may be designed to accumulate carbon as an important ecosystem service in urban areas.

2. Organic carbon in urban soils

Greenspaces in towns and cities are comprised of a mosaic of land-use types, ranging in size from small discrete patches of grassland and trees on roadside verges, along railways and canal sides, to large public parks, playing fields, golf courses and woodlands. The area covered by domestic gardens is important, ranging between 11.3 and 24.9% of the land cover of five UK cities (Loram et al., 2007). The soils supporting these different kinds of greenspaces, although often artificial or modified (Rawlins et al., 2008), represent a significant pool of organic carbon in urban areas, but one that in the UK has not attracted much attention and has not been adequately quantified to date. The vegetation, particularly wooded patches and trees, constitutes a conspicuous organic carbon store within urban greenspaces, but globally soils contain three times more organic carbon than vegetation (Lal, 2008). This is borne-out by some estimates for urban and exurban (including suburban) areas of the USA in which approximately 3.6 Gt of carbon are found in the vegetation, compared to 11.9 Gt in the soils (Churkina et al., 2010).

Previous studies indicate that soil organic carbon storage within urban areas is highly variable, and as the concentration varies non-linearly with depth, the effects of vegetation type or management can only be determined where samples have been taken to the same depth (Table 1). Perhaps surprisingly, there is no evidence that the organic carbon stocks under woodlands are higher than those under grasslands. In Baltimore, USA, soil organic carbon density was slightly higher in garden lawns (6.0 kg m^{-2}) than urban remnant woodland (5.1 kg m^{-2}) to 15 cm depth (Table 1), but these differences became smaller with depth, with a total of 12.2 and 12.0 kg m^{-2} respectively to 1m. In public grasslands organic carbon density to 1m depth was approximately 2 kg m^{-2} lower, but in this case few replicates were taken so it is unclear if these values are representative (Table 1). One of the major uncertainties in these studies is the depth of urban soils and amount of carbon in the subsoil, especially below 1m, and whether this is affected by land use differences such as grassland versus woodland.

Table 1. Mean soil organic carbon density in urban greenspace by soil depth and landuse, with sample numbers in parentheses.

Soil depth	**Mean soil organic carbon (kg m^2)**			**Location**	**Source**
	Public grassland	**Garden lawn**	**Woodland**		
0-10 cm	-	-	6.1 (u.s.)	New York, USA	Pouyat et al (2002)
0-15 cm	-	6.0 (61)	5.1 (37)	Baltimore, USA	Pouyat et al. (2002)
	7.1 (25)	9.7 (25)	-	UK	Rawlins et al. (2008)*
0-30 cm	8.2 (17)^{TC}	-	12.0 (13)^{TC}	Tokyo, Japan	Takahashi et al. (2008)
	3.6 (3)	2.1 (6)	-	Moscow, USA	Smetak et al. (2007)
	-	6.9 (3)	-	Fort Collins, USA	Kaye et al. (2005)
0-53 cm	-	-	6.9 (1)	Baltimore, USA	Groffman et al. (2006)
0-60 cm	-	16.3 (24)	-	Chicago, USA	Jo & McPherson (1995)
0-69 cm	-	-	9.5 (1)	Baltimore, USA	Groffman et al. (2006)
0-100 cm	9.9 (2)	12.2 (18)	12.0 (5)	Baltimore, USA	Pouyat et al. (2006, 2009)

Climate and vegetation together can have major effects on soil carbon. The soil organic carbon concentration to 30 cm depth under drought–resistant vegetation in a garden in Phoenix, Arizona was only 1.0 Kg m^{-2}, and was similar to that under native desert vegetation, whereas in irrigated gardens in the same city the carbon sequestration in soil nearly doubled to 1.8 kg m^{-2} to the same depth (Kaye et al., 2008). Comparisons between amounts of organic carbon in urban soils compared to those of under natural vegetation or agricultural systems thus provide a useful means of evaluating their relative importance. The disturbance of soils and native vegetation on urbanization may release carbon from soils, but with reestablishment of vegetation cover these can re-accumulate organic carbon (Smetak et al., 2007). By the year 2000 the organic carbon density of soils in gardens in Colorado, USA, established in the 1950s, was approximately three times greater than in those established in the 1990s (Golubiewski, 2006). In the UK, soil carbon storage in arable and horticultural soils has been estimated at approximately 4.5 kg m^{-2} (Ostle et al., 2009), which is 36-53% lower than the values reported for public grassland and garden lawns in urban greenspace (Table 1).

Although density of organic carbon can be greater in urban soils when compared to semi-natural or agricultural ecosystems, a substantial proportion of urban space comprises built-over or impervious surfaces such as roads and paving. The artificial surfaces cap formerly active soils, and currently little is known about the fate of organic carbon within these sealed soils, so that the concentrations of organic carbon measured in urban soils should not be extrapolated over the whole urban area. However, Pouyat et al. (2006) assumed an organic carbon density of 3.3 kg m^{-2} (based on data for clean fill soils) for capped soils in the USA, whereas in the UK a value of 0 kg C m^{-2} was assumed for urban areas (including capped and uncapped soils) for a national scale estimate of soil organic carbon storage (Bradley et al., 2005). Built-up urban areas in Europe account for approximately 4% of total landcover (EEA, 2010), within which a large proportion of the soil surface may be sealed, for example in Germany it is estimated that capped surfaces account for approximately 52% of the total urban area (EEA, 2006). However, at a European scale it has been estimated that 9% of the total land cover is capped by artificial surface (Scalenghe and Marsan, 2009), this higher figure will include the entire transport network and buildings outside urban areas, not included in EEA (2010) estimates.

Input of carbon into urban soils is not solely derived from vegetative and microbial biomass. The process of urbanisation and the concomitant human activities result in the deposition of pollutants onto the soils of the greenspaces. This suite of pollutants is derived from vehicle emissions, industry and coal burning and includes a range of heavy metals and organic compounds including black carbon. Black carbon is a highly recalcitrant and altered form of organic carbon, consisting of a range of aromatic hydrocarbon compounds from charred biomass and soot, and which accumulates in soil as it has a very slow rate of decomposition. Urban soils in UK cities have been found to contain black carbon in the range of approximately 4 – 61% of their total organic carbon (Rawlins et al., 2008). This range is based on three cities; Glasgow, Stoke-on-Trent and Coventry, where the mean proportion of black carbon is 22.91% ($\pm$ 2.52, 1 S.E.) and median is 19.63%. The largest proportions of black carbon were all found in the Glasgow samples, where conditioning soil with coal ash was a common practice (Rawlins et al., 2008). The mean and median (16.96%, $\pm$ 2.15 and 14.39 % respectively) are both reduced when the Glasgow data are removed. It is clear that a history of heavy industry and coal burning can leave a strong and lasting legacy of black carbon in urban soils, but if the Stoke-on-Trent and Coventry samples are typical, this is normally < 20% of the soil organic carbon. However, it is clear that black carbon is occasionally the dominant form of organic carbon as in Glasgow (Rawlins et al., 2008) and parts of Stuttgart, Germany, where it provides 72% of soil organic carbon (Lorenz et al., 2006).

Sequestration of organic carbon into urban soils represents an opportunity to reduce net emissions of CO_2, thus reducing the carbon footprint of a city. Research conducted predominantly within the USA has demonstrated the ecosystem service of organic carbon storage provided by urban soils. Within the UK, there is a paucity of data on soil carbon storage in towns and cities, and where estimates have been made, they have been based on rather crude assumptions. For example, carbon concentrations in suburban areas were assumed to be half that found in typical pasture soils (Bradley et al., 2005), an assumption not supported by current data (Table 1). Research now being conducted in the city of Leicester is measuring soil and vegetation carbon storage and sequestration to help inform management of greenspaces in UK urban areas (www.4mfootprint.org). Tree planting and management of existing tree cover is likely to provide the greatest scope for enhanced sequestration and as optimal management practices become established, these should be incorporated into future planning and decision-making at city-wide and national scales.

3. Biochar

Biochar is the highly recalcitrant organic carbon residue that is produced during biomass pyrolysis, typically as part of an energy generating process (Lehmann and Joseph, 2009). Charcoal can be regarded as one type of biochar. Biochar is believed to be highly stable in soil environments, and so represents a potentially valuable sink for biomass carbon (Gaunt and Lehmann, 2008). The application of biochar to soils is known to improve soil fertility in some circumstances, with improvements in water retention and cation exchange capacity (Glaser et al., 2002).

In the UK, the application of biochar to soils is not yet generally permitted (with the exception of charcoal). There is increasing interest in pyrolysis as a process that can be used for the treatment of putrescible waste, which is no longer permitted to go to landfill. Composting effectively only captures 5% of the carbon within the waste, whereas pyrolysis can fix up to 40% of the carbon within waste as biochar. Thus in waste management systems that are designed to have a carbon capture function, biochar is an excellent candidate product, and one that can be considered for application in artificially-modified soils.

The possible use of biochar in urban or engineered soils has scope for providing a number of benefits. First, carbon burial rates of up to 50-140 t ha^{-1} are considered feasible without necessarily any negative impact on the ability of soils to support crop growth (Lehmann et al., 2006). Although the effects of addition of biochar on soil structure from the agricultural or horticultural perspective may be positive (e.g. Busscher et al., 2010), the affect on geotechnical properties remain to be determined (Lehmann and Joseph, 2009). Secondly, improvements in plant growth provide a benefit through reduction in the need for fertilisers or reduced irrigation. Thirdly, there is some evidence that biochar within soils reduces the availability of contaminants, with benefits for contaminated land remediation (e.g. Tomaszewski et al., 2007). In all cases, however, a full risk assessment is needed before biochar is used. For example, risk will vary depending on whether the biochar is derived from plant waste (such as untreated wood waste), or from preservative-treated woods (e.g. some demolition waste), or from mixed domestic refuse.

Although research into the use of biochar in soils is in its early stages, and little thought has been given to its application to urban soils and gardens, there is potential demand from systems that couple waste management with power generation, to give a carbon negative energy source (Matthews, 2008). It is expected that biochar will become increasingly available within the next few years, and that its use in urban soils should be seriously considered.

4. Inorganic carbon in urban soils

The precipitation of carbonate is present in some of the oldest natural soils (Watanabe et al., 2004) and is typical in arid environments where large unbroken layers (often several km^2) occur at the surface. The natural formation of soil carbonates is slow (10^3-10^4 years) and is usually a product of remobilised bedrock material, with no net carbon sequestration from the atmosphere.

Recently research investigating the carbonation of calcium and magnesium silicate minerals to capture atmospheric carbon (Manning, 2008; Lackner et al., 1997) has discovered carbonate formation in laboratory and field experiments. Manning (2008) suggests that accelerated weathering of these materials in soil will capture carbon on a human relevant time scale. Reaction 1 is a simplified approximation of this process, where the CO_2 is derived from the atmosphere (directly or through plants, via photosynthesis, and microorganisms). This incorporates carbon capture into the feldspar ($CaAl_2Si_2O_8$) to kaolinite ($Al_2Si_2O_5(OH)_4$) weathering reaction.

$$CaAl_2Si_2O_8 + CO_2 + 2H_2O \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4 \cdots \Delta Gr = -281 kJmol^{-1}$$

Calcium/magnesium silicate minerals occur naturally in basic igneous rocks, including those quarried for aggregate. They are also produced in cement, and iron and steel making slag, as a result of production processes that decarbonise (calcine) limestone. The available materials and their carbon capture potential are summarised in Table 2, and in total is approximately equivalent to 3 Mt C y^{-1} in the UK. However, the extent of production and their calcium content is not fully accounted. Cement and steel are staple engineering materials specified in most developments. The construction industry contributes 8% to the United Kingdom GDP as a physical manifestation of economic development (HM Government, 2008). Therefore, it is important to mitigate the environmental impact of these materials.

Table 2: The carbon capture potential of calcium rich materials. Estimations are based on CaO content assuming 100% carbonation of the calcium in the material. 1nominal/estimate 2van Oss and Padovani (2003) 3DCLG (2007b) and Lawson et al, (2001) 4Proctor et al., (2000) and EA (2007) 5Lea (1970) pp16, Das et al, (2007) (flue dust can be recycled through fluidised bed reactors, carbonation processes are unknown) and van Oss (2009) 6Russell et al., (2002) 7Goodarzi, (2006) 8USGS (2004).

Material	**Estimated CaO%**	**Estimated UK Production (Mt)**	**Carbon capture potential UK (MtC y^{-1})**
Quarry fines	3[1]	20[1]	0.13
Mine tailings	Unknown	Unknown	Unknown
Cement kiln dust	60-65[2]	1.8	0.23-0.25
Construction waste	14.2[3]	18.5[3]	0.56
Demolition waste	11.9[3]	57.7[3]	1.47
Blast furnace slag	38.34[4]	3[4]	0.25
Steel making slag	44.9[5]	1[4]	0.10
Blast furnace flue dust	4.9[5]	0.28[5]	0.0029
Anthracite ash	3.6[6]	0.22[8]	0.002
Bituminous ash	2.7[7]	2.4[8]	0.01
Total		104.9	2.8

Very little is known about how carbonates form in anthropogenic environments although urban soils are often reported to contain calcium carbonate minerals (Lehmann and Stahr, 2007), probably as a product of carbonation of concrete/cement-derived material that has been deposited in the soil as a consequence of demolition activity.

A recent study (Renforth et al., 2009) investigated two sites in North East England known to contain calcium rich waste material. The first site in Byker, Newcastle upon Tyne, contained substantial quantities of demolition waste throughout the profile (>3m) of the artificial soil (Newcastle City Council). The second site is adjacent to a former steelworks in Consett, Co Durham, which was demolished in 1980. Subsequent site investigations document the occurrence of slag throughout the site (Mayes et al., 2006; Harber and Forth, 2001).

Soils at both sites had an average carbon content of 30±15.3 kg C m^{-2} as calcium carbonate (Renforth et al., 2009) to depths of up to 3m, which is greater than the expected organic carbon content (see above). Stable isotope analysis (C, O) has confirmed the atmospheric origin of the carbon (rather than the remobilisation of rock carbonates; Renforth et al. 2009). Extrapolating the above figure to take into account the area of brownfield land within the UK, it can be speculated that brownfield land stores 12.7 Mt C as calcium carbonate (DCLG, 2007a; Scottish Executive - Statistical Bulletin, 2002). Of course, additional brownfield soils should be investigated to verify this.

5. Implications for engineers and planners

BS 6031:2009 *Code of practice for earthworks* contains a proviso for 'carbon critical design'. However, the associated carbon calculator (available from the Environment Agency website) accounts for the emissions from material production and transport, and does not account for changes in carbon due to soil modification. We suggest that soil carbon may be used to offset the emissions associated with construction. For example, based on the figures presented in this paper, the 2012 London Olympic site (600 hectares) is expected to be able to store around 250 Mt C (30% organic, 70% inorganic carbon) as a consequence of normal and natural soil processes that occur following completion,, compared to the estimate of 1 Mt C released during construction (Commission for a Sustainable London 2012, 2009). Clearly this is justification for careful soil management as part of civil engineering procedures for new developments. For net positive carbon accumulation, anthropogenic soils must contain more carbon than the soils they replace. Mean soil carbon stocks range from 4-10 kg C m^{-2} in arable and grassland soils, between depths to 15 and 30 cm (Hopkins et al., 2009; Ostle et al., 2009; Smith et al., 2000). Therefore, it should be standard practice to measure soil carbon concentration before and after construction, and periodically through the early life cycle of the development, which can be done using relatively inexpensive techniques that are routine in pedology (loss on ignition, thermal analysis, acid digestion etc.) This paper suggests that the maximum carbon capture potential of urban soils using biochar and inorganic carbon accumulation is approximately 7 Mt C y^{-1}, which is over three times the quantity of carbon released during land use change from forest, cropland and grassland soils to UK cities (DEFRA, 2009). The maximum potential of organic carbon accumulation is unknown, but tree planting can sequester 0.6-0.8 kg C m^{-2} y^{-1} into biomass (Read et al., 2009), and carbon storage in UK woodlands soils is estimated to be 25 kg m^{-2} to 1m depth (Bradley et al., 2005), which appears to be considerably higher than values reported for urban woodlands (Table 1). This suggests there may be potential to manage urban woodlands to achieve higher soil sequestration, but further studies are required to establish this.

It is likely that the application of calcium-rich materials derived from demolition in soil (which are required for the precipitation of inorganic carbon and result in increased pore water pH) will exist in mutually exclusive soil horizons to the optimum conditions for organic carbon accumulation (lower bulk densities and pH - Figure 2). Additional research is required to establish appropriate management practices to optimise carbon accumulation in soils. However, research suggests that carbon turnover in forest soils may be less than that in grassland soils in a similar climate (Raich and Tufekcioglu, 2000), although the data for urban greenspace to date provide no confirmation of this (Table 1). Nonetheless, selection of appropriate vegetation in planning and design of new developments may be important. Furthermore, Lal (2003) highlights the importance of management practices on carbon accumulation in agricultural soils, particularly leaving plant residue after harvesting to degrade into the soil and refraining from tilling the soil to limit oxidation. It is probable that soil management practices will have implications for soil carbon accumulation throughout the life cycle of a new development analogous to the implications on planning for environmental impact of a building through its entire life cycle, where the use of a building can far outweigh the environmental impact of the construction process.

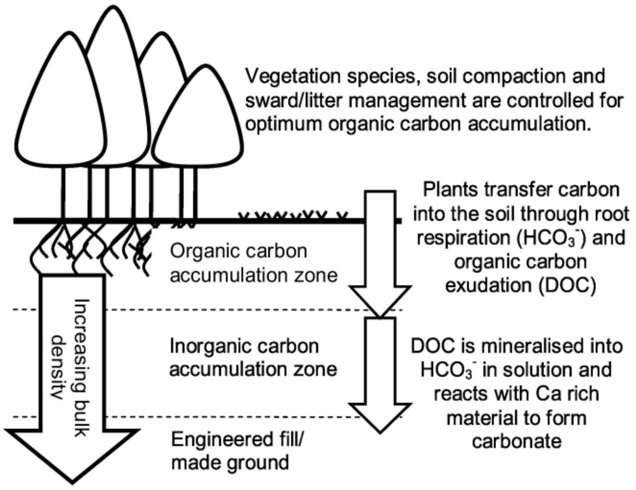

Figure 2: Conceptual model for carbon capture in soils showing distinct functions in soil horizons.

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References

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

BS 6031:2009. (2009) *Code of practice for earthworks.* British Standards Institution

Busscher, W. J., Novak, J. M., Evans, D. E., Watts, D. W., Niandou, M. A. S. and Ahmedna, M. 2010 Influence of Pecan Biochar on Physical Properties of a Norfolk Loamy Sand, Soil Science, 175, 10-14

Churkina, G., Brown, D. G. and Keoleian, G. (2010) 'Carbon stored in human settlements: the conterminous United States', *Global Change Biology,* 16, pp. 135-143.

Commission for a sustainable London 2012. (2009) *Extinguishing emissions.*

Das, B., Prakash, S., Reddy, P. S. R. and Misra, V. N. (2007) 'An overview of utilization of slag and sludge from steel industries', *Resources, Conservation and Recycling,* 50, (1), pp. 40-57.

DCLG. (2007a) *Previously-Developed land that may be available for Development: England 2006.* Crown Copyright (07HC04713).

DCLG. (2007b) *Survey of Arisings and Use of Alternatives to Primary Aggregates in England, 2005 Construction, Demolition and Excavation Waste.* Crown Copyright

DEFRA. (2009) *Inventory and projections of UK emissions by sources and removals by sinks due to land use, land use change and forestry.* Department for Environment, Food and Rural Affairs and the Centre for Ecology and Hydrology

Dupre, B., Dessert, C., Oliva, P., Godderis, Y., Viers, J., Francois, L., Millot, R. and Gaillardet, J. (2003) 'Rivers, chemical weathering and Earth's climate', *Comptes Rendus Geosciences,* 335, (16), pp. 1141-1160.

EA. (2007) *Waste protocols project - Blast Furnace Slag.* Environment Agency

EEA (2006) Urban sprawl in Europe. The ignored challenge. Report No. 10. European Environment Agency, Copenhagen

EEA (2010) 10 messages for 2010. Urban ecosystems. European Environment Agancy, Copenhagen.

Gaunt, J. L. and Lehmann, J. (2008) Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environmental Science and Technology 2008, 42, 4152–4158

Gill, S. E., Handley, J. F., Ennos, A. R. and Pauleit, S. (2007) 'Adapting cities for climate change: The role of the green infrastructure', *Built Environment,* 33, (1), pp. 115-133.

Glaser, B., Lehmann, J. and Zech, W. (2002) 'Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review', *Biology and Fertility of Soils,* 35, (4), pp. 219-230.

Golubiewski, N. E. (2006) 'Urbanization Increases Grassland Carbon Pools: Effects of Landscaping in Colorado's Front Range', *Ecological Applications,* 16, (2), pp. 555-571.

Goodarzi, F. (2006) 'Characteristics and composition of fly ash from Canadian coal-fired power plants', *Fuel,* 85, (10-11), pp. 1418-1427.

Groffman, P. M., Pouyat, R. V., Cadenasso, M. L., Zipperer, W. C., Szlavecz, K., Yesilonis, I. D., Band, L. E. and Brush, G. S. (2006) 'Land use context and natural soil controls on plant community composition and soil nitrogen and carbon dynamics in urban and rural forests', *Forest Ecology and Management,* 236, (2-3), pp. 177-192.

Harber, A. J. and Forth, R. A. (2001) 'The contamination of former iron and steel works sites', *Environmental Geology,* 40, (3), pp. 324-330.

Head, P. (2008) *Entering the ecological age: the engineers role.* Institution of Civil Engineers

HM Government. (2008) *Strategy for sustainable construction.*

Hopkins, D. W., Waite, I. S., McNicol, J. W., Poulton, P. R., Macdonald, A. J. and O'Donnell, A. G. (2009) 'Soil organic carbon contents in long-term experimental grassland plots in the UK (Palace Leas and Park Grass) have not changed consistently in recent decades', *Global Change Biology,* 15, pp. 1739-1754.

Jo, H. K. and McPherson, G. E. (1995) 'Carbon Storage and Flux in Urban Residential Greenspace', *Journal of Environmental Management,* 45, pp. 109-133.

Kaye, J. P., Majumdar, A., Gries, C., Buyantuyev, A., Grimm, N. B., Hope, D., Jenerette, G. D., Zhu, W. X. and Baker, L. (2008) 'Hierarchical bayesian scaling of soil properties across urban, agricultural, and desert ecosystems', *Ecological Applications,* 18, (1), pp. 132-145.

Lackner, K. S., Butt, D. P. and Wendt, C. H. (1997) 'Progress on binding CO_2 in mineral substrates', *Energy Conversion and Management,* 38, pp. S259-S264.

Lal, R. (2003) 'Global Potential of Soil Carbon Sequestration to Mitigate the Greenhouse Effect', *Critical Reviews in Plant Sciences,* 22, pp. 151-184.

Lal, R. (2008) 'Carbon sequestration', *Philosophical Transactions of the Royal Society B: Biological Sciences,* 363, (1492), pp. 815-830.

Lawson, N., Douglas, I., Garvin, S., McGrath, C., Manning, D. and Vetterlein, J. (2001) 'Recycling construction and demolition wastes – a UK perspective ', *Environmental Management and Health,* 12, (2), pp. 146-157.

Lea, F. M. (1970) *The chemistry of cement and concrete [3rd Edition].* London: Edward Arnold Ltd.

Lehmann, J., Gaunt, J. L. and Rondon, M. (2006), Bio-char sequestration in terrestrial systems - a review. Mitigation and Adaptation Strategies for Global Change, 11, 403–427

Lehmann, J. and Joseph, S. (editors), (2009), Biochar for Environmental Management, Earthscan, London, 416pp.

Lehmann, A. and Stahr, K. (2007) 'Nature and significance of anthropogenic urban soils', *Journal of Soils and Sediments,* 7, (4), pp. 247-260.

Loram, A., Tratalos, J., Warren, P. and Gaston, K. (2007) 'Urban domestic gardens (X): the extent & structure of the resource in five major cities', *Landscape Ecology,* 22, (4), pp. 601-615.

Lorenz, K., Preston, C. M. and Kandeler, E. (2006) 'Soil organic matter in urban soils: Estimation of elemental carbon by thermal oxidation and characterization of organic matter by solid-state 13C nuclear magnetic resonance (NMR) spectroscopy', *Geoderma,* 130, (3-4), pp. 312-323.

Manning, D. A. C. (2008) 'Biological enhancement of soil carbonate precipitation: passive removal of atmospheric CO_2', *Mineralogical Magazine,* 72, pp. 639-649.

Mathews, J. A. (2008) 'Carbon-negative biofuels', *Energy Policy*, 36, (3), pp. 940-945.

Mayes, W. M., Younger, P. L. and Aumonier, J. (2006) 'Buffering of alkaline steel slag leachate across a natural wetland', *Environmental Science & Technology,* 40, (4), pp. 1237-1243.

Ostle, N. J., Levy, P. E., Evans, C. D. and Smith, P. (2009) 'UK land use and soil carbon sequestration', *Land Use Policy,* 26, (Supplement 1), pp. S274-S283.

Pouyat, R., Groffman, P., Yesilonis, I. and Hernandez, L. (2002) 'Soil carbon pools and fluxes in urban ecosystems', *Environmental Pollution,* 116, (Supplement 1), pp. S107-S118.

Pouyat, R., Yesilonis, I. and Golubiewski, N. (2009) 'A comparison of soil organic carbon stocks between residential turf grass and native soil', *Urban Ecosystems,* 12, (1), pp. 45-62.

Pouyat, R. V., Yesilonis, I. D. and Nowak, D. J. (2006) 'Carbon storage by urban soils in the United States', *Journal of Environmental Quality,* 35, (4), pp. 1566-1575.

Proctor, D. M., Fehling, K. A., Shay, E. C., Wittenborn, J. L., Green, J. J., Avent, C., Bigham, R. D., Connolly, M., Lee, B., Shepker, T. O. and Zak, M. A. (2000) 'Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Industry Slags', *Environmental Science & Technology,* 34, (8), pp. 1576-1582.

Raich, J. W. and Tufekcioglu, A. (2000) 'Vegetation and soil respiration: Correlations and controls', *Biogeochemistry,* 48, (1), pp. 71-90.

Rawlins, B. G., Vane, C. H., Kim, A. W., Tye, A. M., Kemp, S. J. and Bellamy, P. H. (2008) 'Methods for estimating types of soil organic carbon and their application to surveys of UK urban areas', *Soil Use and Management,* 24, (1), pp. 47-59.

Read, D. J., Freer-Smith, P.H., Morison, J. I. L., Hanley, N., West, C. C. and Snowdon, P. (eds). (2009). *Combating climate change- a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. the synthesis report.* The Stationary Office, Edinburgh. pp. 1-17.

Renforth, P., Manning, D. A. C. and Lopez-Capel, E. (2009) 'Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide', *Applied Geochemistry,* 24, (9), pp. 1757-1764.

Rogner, H.-H., D. Zhou, R. Bradley, P. Crabbé, O. Edenhofer, B.Hare, L. Kuijpers and Yamaguchi, M. (2007) *Introduction. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: IPCC

Russell, N. V., Méndez, L. B., Wigley, F. and Williamson, J. (2002) 'Ash deposition of a Spanish anthracite: effects of included and excluded mineral matter', *Fuel,* 81, (5), pp. 657-663.

Scalenghe, R. and Marsan, F. A. (2009) 'The anthropogenic sealing of soils in urban areas', *Landscape and Urban Planning,* 90, (1-2), pp. 1-10.

Scottish Executive - Statistical Bulletin. (2002) *Scottish Vacant and Derelict Land Survey 2001.* (ENV/2002/1).

Smetak, K. M., Johnson-Maynard, J. L. and Lloyd, J. E. (2007) 'Earthworm population density and diversity in different-aged urban systems', *Applied Soil Ecology,* 37, (1-2), pp. 161-168.

Smith, P., Goulding, K. W. T., Smith, K. A., Powlson, D. S., Smith, J. U., Falloon, P. and Coleman, K. (2000) 'Including trace gas fluxes in estimates of the carbon mitigation potential of UK agricultural land', *Soil Use and Management,* 16, (4), pp. 251-259.

Takahashi, T., Amano, Y., Kuchimura, K. and Kobayashi, T. (2008) 'Carbon content of soil in urban parks in Tokyo, Japan', *Landscape and Ecological Engineering,* 4, (2), pp. 139-142.

Tomaszewski, J.E., Werner, D., Luthy, R.G., 2007. Activated carbon amendment as a treatment for residual DDT in sediment from a superfund site in San Francisco Bay, Richmond, California, USA. Environmental Toxicology and Chemistry, 2143–2150.

U.S. Department of the Interior and U.S. Geological Survey (2004) *Minerals Yearbook* [Online]. Available at: http://minerals.usgs.gov/minerals/pubs/country/index.html#pubs (Accessed: 14/01/09).

van Oss, H. G. (2009) *Iron and Steel Slag.* United States Geological Survey

van Oss, H. G. and Padovani, A. C. (2003) 'Cement manufacture and the environment', *Journal of Industrial Ecology,* 7, (1), pp. 93-126.

Watanabe, Y., Stewart, B. W. and Ohmoto, H. (2004) 'Organic- and carbonate-rich soil formation 2.6 billion years ago at Schagen, East

Transvaal district, South Africa', *Geochimica et Cosmochimica Acta,* 68, (9), pp. 2129–2151.