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Understanding and fostering soil carbon sequestration

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Management of soil carbon sequestration in urban areas

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1 Introduction

Urban areas are characterised by a high population density and built infrastructure. According to a global, people-based definition, urban centres are places with at least 1500 inhabitants per square kilometre and a total population of at least 50 000 people (EC, 2022). For the first time in history, in 2007, more people lived in urban than in rural areas with the urban population expected to reach 60.4% of the global population by 2030 (UN-Habitat, 2020). Urban soils are vital components of urban ecosystems (Li et al., 2018), although urbanisation also leads to soil loss following the construction of buildings and (grey) infrastructures.

Given continued urban growth, urban soils are becoming increasingly important for the ecosystem services they can deliver (O'Riordan et al., 2021). These range from potential roles in improving air quality, water quality and management, recreational services, through to organic carbon sequestration to combat climate change (Jansson, 2013). Promoting ecosystem services includes a diverse range of practices to improve soil structure and organic

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matter content, for example, through bioremediation of degraded soils, adding compost or biosolids or planting vegetation (Logsdon et al., 2017). Enriching urban soils with organic matter requires putting the focus on recycling waste materials within urban areas under the framework of a circular economy rather than relying on importing organic matter from outside. Indeed, it has recently been suggested that locally available resources should be used to restore soils and to revitalize metropolitan areas for improving the overall quality of life for a rapidly growing urban population (Kumar and Hundal, 2016).

Urban soils may have substantial soil organic carbon (SOC) storage potential per unit area (Pouyat et al., 2006). Data from 116 cities worldwide showed that the total carbon (C) content of urban soils was 1.5–3 times higher and that SOC storage occurred at greater depth than in some rural mineral soils, particularly in residential areas (Mazurek et al., 2016; Vasenev and Kuzyakov, 2018). Urban soils also contain substantial amounts of inorganic C and have been identified as global hotspots in terms of soil C storage, partly because they may have the potential to gain or lose C rapidly (Riddle et al., 2021). Some types of urban structures and carbon types, which may be found in urban environments, are shown in Fig. 1.

This chapter aims to present the urban soil and carbon types and the management of SOC sequestration in different urban infrastructures. We will analyse SOC sequestration in man-made and semi-natural (infra-) structures. In the context of a circular economy, this chapter also addresses the use of recycling strategies of urban waste materials to foster SOC sequestration.

Urban infrastructures

Grey infrastructures

- Water retention systems
- Roads
- Piplines

Green infrastructures

- Parks, gardens, lawns
- Urban forests
- Community gardens
- Green roofs
- Bioretention systems

Carbon types

- Inorganic C (SIC)
- Organic C (SOC)
- Plant litter
- Compost
- Black C
- Plastic
- Organic contaminants

Figure 1 Infrastructures and carbon types, which may be found in an urban context.

2 Characteristics of soils in urban environments

Urban soils created as part of the process of urbanisation are strongly affected by human activities and are typically heterogeneous in structure, composition and properties (Rossiter, 2007; Lorenz and Lal, 2015). They were defined as a continuum depending on the degree of anthropogenic alterations (Pouyart and Treammell, 2019) and are included in soil classification systems as Technosols and Anthrosols (WRB, 2014). Human activity influences urban soils through material movement and redistribution, transport and deposition, introduction of man-made materials and accumulation of toxic compounds (Burghardt et al., 2015). Urban soils include a wide range of different soil types. Relict 'native' soil is presently protected from urban development, in green, semi-natural spaces such as parks and urban forests. These areas may contain a mix of local and imported soils designed to support trees and other plants. Additionally, urban soils may be composed of highly heterogeneous combinations of materials resulting from building or industrial activity. These may be characterized by a high content of synthetic materials such as glass, metal, plastic and so on, frequently with high levels of chemical contamination (Craul, 1985; Li et al., 2018; Sager, 2020; O'Riordan et al., 2021). The latter types of soil are usually characterised by disturbed structure, high compaction, reduced pore space, limited moisture, higher average temperature and pH, high levels of toxic pollutants, low organic matter content and limited vegetation cover (Craul, 1985). In general, urban soilscape is complex and influenced by past and current human interventions, pre-urban geomorphology and hydrography (Delbecque et al., 2022). A recent study concluded that urban soils are global hotspots of soil C sequestration due to high stocks and accumulation rates (Vasenev and Kuzyakov, 2018). Different forms of C with contrasting stability and functions are present in urban soils. They include SOC derived from plant litter, soil inorganic carbon (SIC), black carbon derived from combustion processes and xenobiotic carbon – such as plastics – polycyclic aromatic hydrocarbons and other organic pollutants (Fig. 1). Management of soil C in these systems is thus complex but relates in many cases to best management practices recommended for soils in rural areas (refer to Chapters 15–23 of this book).

3 Fostering soil organic carbon sequestration in urban infrastructures

In urban areas, two types of infrastructures are present (Fig. 1): (1) grey infrastructures, which are engineered structures that use concrete and steel and generally seal floors; and (2) green infrastructures, which comprise natural, semi-natural and artificial areas for vegetation with and without trees (such as parks, gardens and road-side verges) and also man-made systems such as bioretention systems and green roofs (Tzoulas et al., 2007). Management activities to foster SOC sequestration need to be specific in each of these different infrastructures.

3.1 Grey infrastructures

Construction of buildings and infrastructure such as roads often leads to sealing of the soil surface with impervious materials such as concrete or tarmac (Scalenghe and Marsan, 2009). Such sealing largely influences biogeochemical cycling and soils under impervious surfaces are often depleted in SOC compared to open soils (Raciti et al., 2012; Wei et al., 2014). Soil organic carbon losses may occur following decomposition of organic matter beneath the impervious surface or through topsoil removal and erosion during the construction process (Wei et al., 2014). Sealing disrupts the complex interactions between the atmosphere, plants and soil, reducing the capacity of the soil to deliver ecosystem services such as reducing runoff, filtering pollutants and sequestering SOC.

Therefore, soil sealing should be avoided and wherever possible, semi-pervious materials such as gravel, stone aggregates, porous asphalt or wood chip should be used to allow for water infiltration and potential plant growth (Scalenghe and Marsan, 2009). It has been shown that de-sealing can favour SOC storage and other soil ecosystem services by rapid recovery of physical, chemical and biological properties following the establishment of pioneer vegetation (Renella, 2020).

3.2 Gardens, parks, street trees and lawns

Urban parks, gardens and lawns are often established on natural soils, which had been present before urbanisation or had been imported from rural areas. These green infrastructures are usually managed by regular cutting (and disposal of cuttings), weed removal (often using herbicides), irrigation and application of synthetic fertilisers. These intensive management practices have environmental costs and trade-offs for SOC sequestration (Chapter 6 of this book). For example, an evaluation of SOC sequestration and greenhouse gas (GHG) emissions from turfgrass in athletic fields and ornamental lawns in urban parks found that GHG emissions through fuel use from machinery, fertilisation and irrigation outweighed SOC sequestration (Townsend-Small and Czimzik, 2010). In addition, taking organic matter out of the system, following management activities such as mowing and removal of grass clippings and/or cleaning measures such as tree leave removal in autumn, was also found to reduce SOC contents (Yoon et al., 2016).

In order to manage SOC in parks, gardens and lawns sustainably, semi-natural gardens and lawns requiring less intensive management should be established. High tree density has been found to be related to SOC storage (Mexia et al., 2018). More sustainable practices include retention of plant litter such as tree leaves and grass cuttings to provide continuous soil cover, improving moisture retention and nutrient cycling which likely also reduces the need for irrigation and fertilisation. Soil organic carbon storage in park soils may be enhanced by appropriate management of plant litter. Where grass clippings and tree leaves are not contaminated (e.g. by pollutants from traffic emissions), organic waste treatments such as composting can be used. Increased SOC storage was, for example, achieved in the Seoul Forest Park, where litter was added back to soils after composting (Bae and Ryu, 2015).

3.3 Urban forests

Urban forests provide a variety of essential ecosystem services, including decreasing air, water and noise pollution, mitigating flood risk and providing recreational areas (Escobedo et al., 2011; Roy et al., 2012). Organic carbon sequestration is a climate change mitigation service of urban forests in addition to their function of reducing the urban heat island effect (Kleerekoper et al., 2012). While some studies have shown that total SOC storage in urban forests is similar to those of rural ones (Pouyat et al., 2002), other studies found that SOC sequestration is depending on tree density (Lv et al., 2016). Moreover, more significant proportions of recalcitrant C have been found in urban forest soils than in rural ones due to poorer quality leaf litter, enhanced mineralisation of readily available SOC due to non-native earthworms and higher soil temperatures (Groffman et al., 1995). According to Pouyat et al. (2002), urban forests could potentially sequester and store more SOC than rural forests.

While relatively few studies exist that specifically address soil C management in urban forests, their higher SOC stocks compared to those of other urban sites may partly be explained by their age and a management legacy of wastewater irrigation, liming and charcoal application (Foti et al., 2021). Long-term studies of forest management strategies of rural forests recommend increasing productivity, for example, through afforestation and planting of fast-growing tree species, which have immediate effects on SOC sequestration (Jandl et al., 2007, Chapter 19 of this book); however, in an urban context, environmental and political constraints may limit such practices. For example, the presence of construction materials leading to high carbonate contents, limited water storage capacity and/or presence of pollutants in urban soils may limit the species able to grow under such conditions. Sustainable forest management after their establishment should include minimal disturbance of stand structure and soils to promote SOC retention (Jandl et al., 2007, Chapter 19 of this book).

Application of compost and/or mulching could increase urban forest SOC storage (Brown et al., 2012; Beesley, 2012), as could biochar; however, it is not known how management practices might impact inorganic C from carbonate reactions (Lorenz and Lal, 2015).

3.4 Green roofs

Green roofs, green walls and vertical gardens have been introduced into building environments because of their positive effects such as insulation, air quality, soundproofing and as a way of improving the ecological footprint of cities (Getter et al., 2009).

They can also be used to sequester SOC. It has been found that green roofs can potentially store about 375 g m^2 SOC with substrate contributing to about one-third of the storage (Getter et al., 2009). This highlights the importance of the type and depth of the growth substrate as well as the proportion of inorganic and organic materials used when generating the substrate (Lata et al., 2018). A 10–20% organic component seems optimal for plant growth (Ondono et al., 2016). Local waste materials such as compost and municipal sewage sludge have been used for green roof construction in the UK (Molineux et al., 2009) and China (Luo et al., 2015). The addition of sewage sludge to the substrate increased SOC sequestration up to 13 kg SOC per m^2 (Luo et al., 2015).

It is important to take the impact of management intensity into account. Extensive green roofs are light weighted and typically support herbal vegetation on shallow substrates requiring minimal maintenance. Intensive green roofs are heavier with a deeper layer of growing substrate to support a wider variety of plant types, including shrubs and trees (Besir and Cuce, 2017). Soil organic carbon storage may thus be higher in intensively managed green roofs but may also require more external inputs in terms of irrigation, fertilisation and overall maintenance, thus also increasing the trade offs of SOC sequestration (Chapter 6 of this book).

Whilst green roofs have been widely used in temperate regions such as Northern Europe, their use in arid regions (such as the Mediterranean) is more challenging without potentially intensive irrigation (with its associated environmental costs). One potential solution is the use biocrusts, desert-based communities composed of a complex mosaic of cyanobacteria, green algae, lichens, mosses, microfungi and other bacteria. These are well adapted to survive drought conditions with minimal substrates and may be suited for SOC sequestration on green roofs in drier climates (Paço et al., 2014).

3.5 Bioretention systems

Bioretention systems are used to channel, retain and purify rainwater. They use vegetation to moderate water flow and act as a filter to improve water quality. Cities such as New York have invested significantly in these systems

(The City of New York, 2010; Joyner et al., 2019). The type and amount of organic materials used to construct bioretention systems such as bioswales affect their water infiltration, filtration properties and also SOC sequestration potential. Biochar, for example, has a high adsorption potential for contaminants and may sequester SOC in the long term (Biswal et al., 2022). A potential problem to avoid in their construction and maintenance is nitrate leaching from use of nitrogen-rich vegetation supplemented by fertilisers (Shetty et al., 2018). Despite the role bioretention systems could play in SOC sequestration, their SOC sequestration potentials have not yet been studied in detail (Gill et al., 2017).

4 Organic waste recycling to foster soil organic carbon storage in urban soils in the context of a circular urban economy

Organic matter is employed in many urban soils for restoration, construction purposes and also green infrastructure development. In particular, Technosols are man-made engineered structures with technic material. They contain artefacts or extracted unconsolidated material and bedrocks, and may have a sealing layer or a geo-membrane (Burghardt et al., 2015). Construction and demolition waste may be re-used together with organic waste for their construction. Technosols are an alternative to importing soil for restoring degraded urban areas (Deeb et al., 2017; Barredo et al., 2020; Fabbri et al., 2021). They have been used, for example, in urban community gardens in New York City (Egendorf et al., 2018). Moreover, Technosols are used for green infrastructure construction (Deeb et al., 2020) and also urban farming is often based on specific engineered systems, such as lasagne gardening (Lanza, 1998), consisting of different layers of materials. In many cities, rooftop farming is nowadays practised, and management of organic matter in soils or engineered growth substrates used for food production is thus of primary importance in urban agriculture. Organic materials used as growth substrates in urban agriculture may include bark, composted materials including green (yard) wastes, municipal solid wastes and even sewage sludge (Carlile et al., 2015).

The type of organic material determines the stability of SOC as well as other soil properties. High SOC concentrations lead to soil decompaction as well as increased drought resistance through greater water retention and rooting depth (Robin et al., 2018) but may also lead to groundwater contamination due to N and P leaching and production of greenhouse gases. In order to optimise the properties of Technosols, the presence of worms and plants is required (Deeb et al., 2017). It has been shown that the earthworm species *Dendrobaena veneta* was able to improve properties such as plant available water content in Technosols (Ulrich et al., 2021). Earthworm activity can also promote SOC stabilisation (Le Mer et al., 2020). Optimising SOC sequestration in Technosols requires the right combination of organic, inorganic and biological components. Generally, the addition of more than 30% of organic matter should be avoided (Deeb et al., 2020). It is also important to consider the SIC content of construction material as active dissolution and redistribution processes of calcium carbonate are frequently observed in Technosols under humid climate conditions (Prokof'eva et al., 2021).

Materials for Technosol construction should ideally originate from inside the urban setting. Organic materials should be transformed by recycling organic wastes from urban areas into bio-fertilisers and soil amendments to create a circular local economy with minimal environmental impact (Tedesco et al., 2017; Moinard et al., 2021, Fig. 2).

This is all the more important given the scale of organic urban waste and the limited access of urban farmers to resources such as organic matter, fertilisers and water. Therefore, food production as well as soil restoration and SOC sequestration in urban agriculture may be favoured by recycling of bio-solids and bio-liquids produced by human settlements (Lal, 2017). Policy

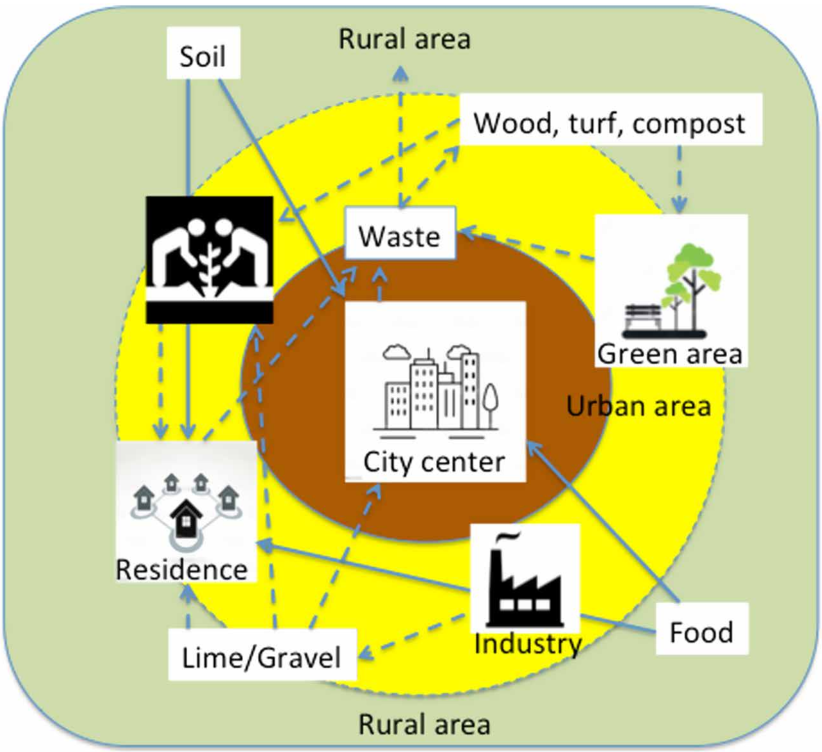

Figure 2 Material flows in an urban context (inspired by Vasenev and Kuzyakov, 2018).

support and strategies for urban agricultural development are often missing (Crush et al., 2012) although they are extremely important in urban areas, where SOC sequestration should be integrated to reduce their C-footprint.

Organic urban waste can be categorised in various ways such as food waste, garden waste and animal waste. The volume and type of such waste vary widely. Organic waste forms more than 50% of the total municipal solid waste generated in low and middle-income countries of West Africa (Henry et al., 2006; Couth and Trois, 2010) and 30% of municipal solid waste in developed countries (Hoornweg et al., 2013). The European Union, for example, generates around 88 million tonnes of food waste each year, coming mainly from homes and food retail outlets (Stenmarck et al., 2016), while around 17% of total global food production amounting to 931 million tonnes may be wasted (UNEP, 2021) and thus available for recycling.

Recycling this waste is a major challenge for municipal authorities (Pollans et al., 2017; Chen et al., 2020). Some European countries have schemes to separately collect and sort organic municipal waste, for example, Germany, Austria, Belgium and France. Some municipalities go further and encourage citizens to recycle organic waste themselves. The City of Paris, for example, distributes composting units and provides guidance on their use. However, in some parts of the world, such as Asia and the Pacific, a large amount of municipal waste still goes to landfills (Horrocks et al., 2016; Jara-Samaniego et al., 2017). This has significant negative environmental impacts in terms of odours, methane emissions, soil and groundwater contamination (Xiaoli et al., 2007; Prechthai et al., 2008) and also is a missed opportunity to increase SOC storage.

In the US, for example, recycling of food waste has doubled since 2010 but is still at a very low level (5%). A pioneer in establishing a progressive food waste policy was the State of California, which introduced the Integrated Waste Management Act in 1989. This law has been put into practice by the City of San Francisco, which successfully reduced waste going to landfills by 50% by 2000 and is currently aiming to achieve zero food waste (AzCentral, 2017). Other cities such as New York have announced new rules requiring restaurants and grocery stores to recycle food waste (Recycling Today, 2018). Another successful example is the green exchange programme (Cambio Verde) developed by the City of Curitiba (Brazil) in 1989, in which organic wastes are collected by people living in slums and exchanged for surplus food produced on smallholder farms. Korea has developed a zero food waste system, which allows onsite treatment of organic wastes in apartment complexes (Oh and Lee, 2018).

There are a range of techniques to transform organic waste into organic fertilisers (Chapter 9 of this book). Briefly, these include anaerobic digestion, composting, vermicomposting (using earthworms) and thermal treatment to create biochar. Composting has been widely used in many low-income countries in West Africa, Asia and South America to process organic waste

(Zurbrügg et al., 2005; Hoornweg and Bhada-Tata, 2012; Jara-Samaniego et al., 2017). Advanced composting techniques can now transform organic waste into bio-fertiliser in as little as 12 days (Wei et al., 2021). A key challenge is removing chemical and biological contaminants from mixed wastes (Farrell and Jones, 2009). Suitable composting strategies include separating the waste into pools with different compositions and co-composting with bulking agents, mineral, organic or microbiological compounds (Barthod et al., 2018). Vermicomposting has also been found to reduce contaminant levels in organic urban waste (Singh et al., 2011). Co-composting and co-vermicomposting also shorten processing times, help to stabilise mineral content (especially available N) and promote SOC sequestration (Vidal et al., 2020). Soil organic carbon residence time in the soil can be increased by mixing with recalcitrant compounds such as biochar before field application (Ngo et al., 2016).

5 Conclusion

In urban areas, the nature and distribution of soil C are highly heterogeneous, ranging from organic matter in soils of parks or lawns to carbon-rich artefacts and contaminants in man-made structures. Similar to rural areas, SOC sequestration in urban soils is influenced by land-use and management practices. Extensive management of urban infrastructures may counteract trade offs of SOC sequestration in form of greenhouse gas emissions, water use and pollution. Although many urban soils may contain substantial amounts of C, their SOC sequestration potential has been poorly quantified. Improving SOC sequestration may be necessary to secure the broad range of ecosystem services that urban soils can deliver. More generally, the challenge of fostering SOC sequestration in urban soils needs to be seen in the wider context of creating a more sustainable circular urban economy in which organic materials are recycled to reduce waste and at the same time improve the quality of urban soils. This requires skills in planning, governance, communication and education to develop and implement management practices and technologies aiming to protect and foster SOC storage without generating trade-offs.

6 Where to look for further information

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