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The ecosystem services of urban soils: A review

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ABSTRACT

The expansion of urban areas worldwide is increasing the anthropogenic impact upon soil and highlights the important role of urban areas in supporting a sustainable future. As such, urban soils are becoming more important in the delivery of a broad range of ecosystem services (ESs), including carbon storage and climate regulation, biomass provision for food and water flow regulation, and recreational benefits. In this review, we aim to support the development of this emerging research area and, subsequently, support the improved treatment and management of urban soil and ES delivery. We present a systematic review of which ESs have been studied and examine trends in research using a co-occurrence analysis of key terms. We then provide a summary review of current knowledge on ESs and identify the gaps in knowledge. Our review highlights that this is a young, but growing, field of research, with a marked increase in publications since 2014. We found that supporting processes and regulating services were most commonly studied, with 88% and 71% of the papers relating to quantitative studies addressing these, respectively. Cultural, provisioning and water-related ESs were relatively understudied, suggesting key gaps for future research. However, this may be attributable to a disconnection between academic communities rather than a lack of knowledge. Fewer than 20% of quantitative studies addressed more than two ESs simultaneously, leading us to suggest that urban soil multifunctionality is a key area for future research, and highlighting the need to integrate understanding of urban soil ESs across disciplines and professions. In addition to this overarching suggestion, we propose six research gaps and opportunities: further research into biomass provision for food, water-related ESs and cultural ESs; greater geographical representation; further interconnection between research and practitioner communities; and a focus on the future drivers of soil change in urban environments.

1. Introduction

More than half of the world's population currently live in urban areas, defined as areas with a population of 10,000 residents or more (DEFRA, 2005), and this is projected to reach almost 70% by 2050 (United Nations, 2019). As urban populations increase, the ability of the urban environment to provide liveable places and support resilient ecosystems becomes more important (Biggs et al., 2012). This, in addition to the risks to human health posed by climate change and air pollution (Jacob and Winner, 2009; Heaviside et al., 2017; O'Donnell and Thorne, 2020), means that it is ever more crucial that we consider how well urban environments are able to maintain the ecosystem services (ESs), namely the benefits people obtain from ecosystems (MEA, 2005), that they currently deliver.

Soils play a fundamental role in providing numerous, vital ESs (Dominati et al., 2010; Adhikari and Hartemink, 2016; Jónsson and Davíðsdóttir, 2016; Greiner et al., 2017), and the importance of soil in providing ESs in urban areas is becoming increasingly recognised within the soil science community (Lehmann and Stahr, 2007; Pavao-Zuckerman, 2008; Lal and Stewart, 2017; Ziter and Turner, 2018; Bray and Wickings, 2019). In this review, we consider urban soils to be all soils located within urban areas. Urban soils are included within SUITMA (Soils of Urban, Industrial, Traffic, Mining and Military Areas), defined as soils strongly modified by human activities with drastic changes in composition and function, though in urban areas, they can include both highly-transformed soils and pseudo-natural soils (Morel et al., 2015). In this review, we limit our focus to soils within urban areas to enable a focus on the provision of ESs in areas where the majority of

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people live. In urban areas, urban soil underpins many ESs that provide importance for human wellbeing and urban resilience (Gómez-Baggethun et al., 2013; Haase et al., 2014; McPhearson et al., 2015). Locally, these services include flood mitigation, buffering the urban heat island effect, capturing air pollution, physical support for infrastructure, urban food growing and access to greenspace for mental and physical health; whilst at local and global scales, they contribute to nutrient cycling and carbon (C) storage.

Urban soils are able to provide many of the same ESs as non-urban soils (Pavao-Zuckerman, 2012; Morel et al., 2015; Pouyat et al., 2020). At present, however, there is relatively limited knowledge on their quantification as compared to non-urban soil ESs. Much work since the development of The Economics of Ecosystems and Biodiversity (Kumar, 2010) and The Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2018) has placed a focus on ecosystem goods and services that are directly beneficial to humans, allowing the economic valuation and accounting of ES. Whilst this valuation makes the concept useful to policy and decision makers, there remains a need to further understand specifically how urban soil supports ESs. Research into urban soil ESs is still in its infancy and much work is at the level of soil processes, functions or properties. As such, it is necessary to focus on, and distinguish between, supporting processes that drive soil functioning, and soil ESs that are directly beneficial to humans (Dominati et al. (2010); Baveye et al. (2016).

The study of urban soil ESs is slowly gaining momentum, often with a theoretical focus on the potential ESs that can be provided (Morel et al., 2015; Vasenev et al., 2018), or through improving methods of quantification and integration into planning (Blanchart et al., 2018; da Silva et al., 2018). However, there remains a gap in bringing together what is currently known within the research community about urban soil ES provision. There is a need to gain a better understanding of which ESs are provided by urban soils; the extent to which individual ESs have been studied; how they will be altered by future drivers of change such as climate change; and how we can manage urban soils to deliver ES, now and in the future. This review serves to address these needs by bringing together the literature on urban soil ESs to provide an understanding of what we currently know, analysis of the trends in research and an identification of gaps in knowledge.

We firstly present a bibliometric analysis of the urban soil ES literature, analysing which ESs have been most studied, where and at what soil depth; and explore the structure of the research community using a co–occurrence analysis of key terms. We then provide a summary review of knowledge on individual ESs delivered by urban soils, reviewing what has been studied and where the gaps in knowledge are. Lastly, we make suggestions for the direction of future research to aid the understanding of urban soil ESs and optimise their provision.

2. Material and methods

2.1. Literature search

We performed a literature search to gain an understanding of which urban soil ESs have been most studied and where. There was a focus on the use of ES terminology to identify studies that employed an ES framing. We also included terminology associated with soil processes and functions in addition to ES, as these terms are still used interchangeably within the soil science community (Schwilch et al., 2016), and the ideas of ESs and ecological functions are closely related (Vasenev et al., 2018). This interrelation is recognised by Baveye et al. (2016) who stressed that it is important to consider both soil functions and ecosystem services, so long as they are articulated in relation to soil properties and processes (Bünemann et al., 2018).

A search of English language literature was performed in April 2020 on Web of Science for urban AND soil* in the title, combined with "ecosystem service*" in the topic (title, abstract and keywords). A second search was run for "urban soil*" AND "ecosystem service*" in the topic. A third search was run for ("soil process*" or "soil function*") AND urban* in the topic. These three searches were then combined using the OR operator. The complete search had the following search string:

(TI=(urban AND soil*) AND TS="ecosystem service*") OR (TS=("urban soil*" AND "ecosystem service*")) OR (TS=(("soil process*" OR "soil function*") AND urban*))

The same search was run on Scopus and documents were collated together. Book chapters, meeting abstracts and conference reviews were excluded. An initial review of the documents was undertaken and those without an urban focus were removed, which left 178 papers that were relevant to urban soil and ES.

2.2. Data analysis

The literature was first separated into three categories: those that measured ESs through empirical data or modelling studies were referred to as 'quantified' papers; those that only discussed ESs in relation to urban soils were referred to as 'discussion' papers; and those that did not specifically quantify or discuss ESs were referred to as 'general urban soil' papers. Where papers had collected data that provided information about the listed ESs, whether explicitly described as an ES or not, they were classed as 'quantified' papers. Review papers were included in the 'discussion' or 'general urban soil' papers.

We undertook the bibliometric analysis on all categories of literature. We then carried out more detailed analysis on the 'quantified' papers to investigate which ESs had been studied, which were commonly studied together, and which soil depths were most recorded. The findings in these 'quantified' papers were then used to present the summary review of urban soil ESs.

To capture how urban soil supporting processes and ESs are being studied and at which level, the framework of soil ESs proposed by Dominati et al. (2010) was used (Table 1). The framework distinguishes between supporting processes that drive soil functioning (such as nutrient cycling, water cycling or soil biological activity), and ESs that are directly beneficial to humans, which include provisioning, regulating and cultural services. The definitions given by Dominati et al. (2010) were used to categorise the supporting processes and ESs identified in the 'quantified' papers, and are provided in the supplementary material.

Some studies measured both a supporting process (e.g. microbial activity) and a regulating service that is related to the supporting process (e.g. C storage); in these cases, the papers were classed as measuring both. While these processes and services are interlinked, they have been analysed in this way to build an understanding of which supporting processes and ESs have been studied in detail, and in addition, how researchers refer to them and approach studying them.

2.3. Co-occurrence analysis of key terms

The titles and abstracts of the 178 papers collected in the literature search were analysed using the VOSviewer software (Van Eck and Waltman, 2010) to identify the most common terms and co–occurrences

Table 1
The list of soil supporting processes and ecosystem services given in Dominati et al. (2010) used in this manuscript.

Category	Supporting Process or Ecosystem Service
Supporting Processes	Nutrient cycling; water cycling; soil biological activity
Provisioning ESs	Food, wood and fibre; physical support; raw materials
Regulating ESs	Flood mitigation; filtering of nutrients; Biological control of pests and diseases; Recycling of wastes and detoxification; Carbon storage and regulation of greenhouse gas (GHG) emissions
Cultural ESs	Spirituality; knowledge; sense of place; aesthetics

between them. A threshold of 5 occurrences of each term was used to identify common terms in the literature (one count per title/abstract rather than all counts of each term). A thesaurus file was used to simplify terms for consistency (such as SOC to soil organic carbon, or soil C to soil carbon). A relevance score was applied by the software that filters out generic terms such as 'method' or 'result', and which helps cluster together topic-specific terms (Van Eck and Waltman, 2011). The co–occurrence network is presented to show terms with the most occurrences, links between them and where clusters form between the terms. The clusters were set to a minimum of 25 terms per cluster to enable themes to be visualised.

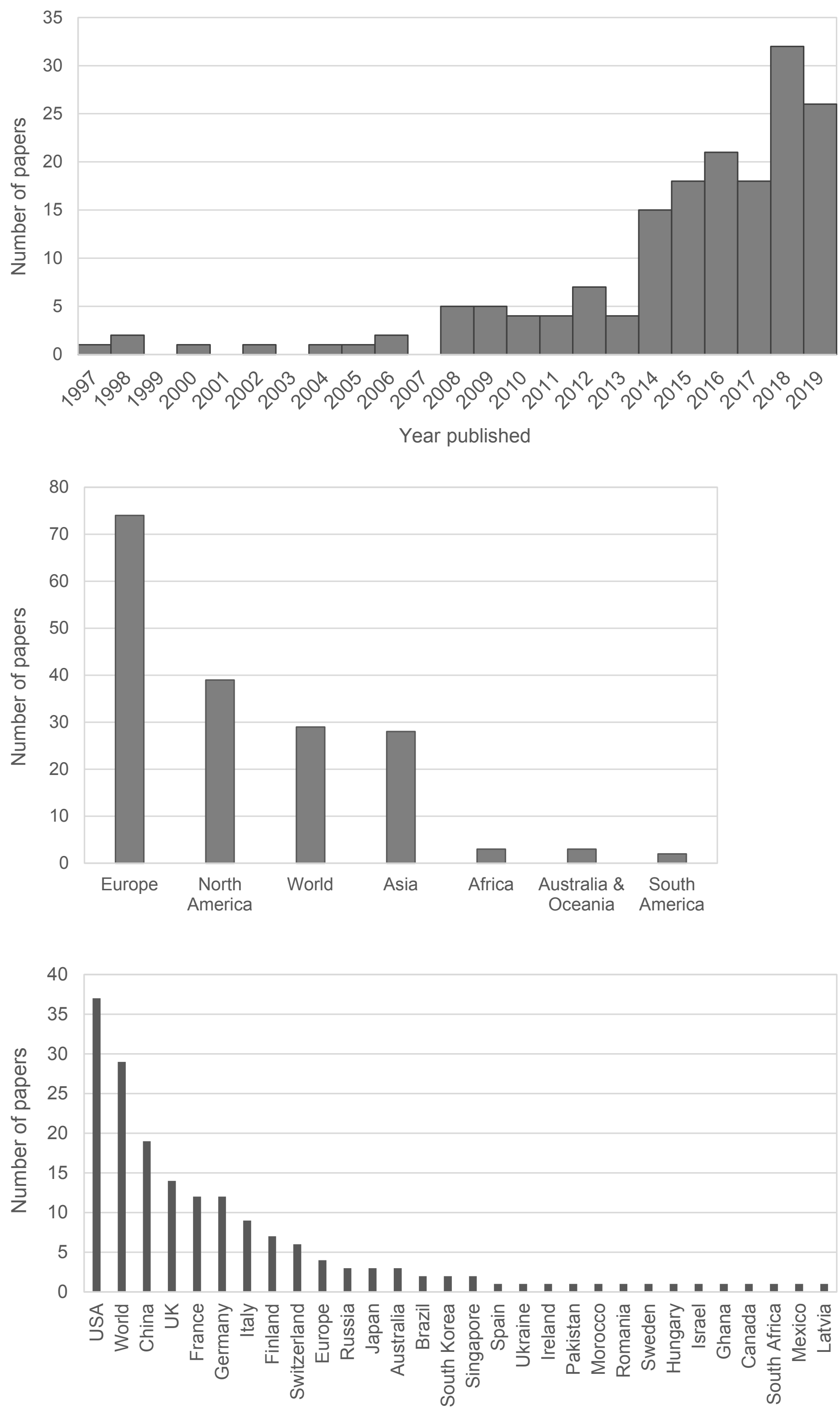

Fig. 1. 1a. Number of papers published between 1997 and 2019 using the search string for urban soil and ecosystem services; 1b. number of papers published by global region; 1c. number of papers published with scopes at different geographical scales: country, continent or global.

3. Results and discussion

3.1. Analysis of urban soil ES literature

3.1.1. Bibliometric analysis of literature

The distribution of the literature with publishing year and geographical scope is illustrated in Fig. 1. The number of publications on urban soil ESs is relatively small and recent compared to that of soil ESs, with the oldest paper found dating from 1997. Papers studying urban soil ESs did not become more common until 2014, after which the number of publications generally increased, with the most published in 2018 (Fig. 1a).

Much of the literature identified relates to studies in Europe (42%) as shown in Fig. 1b. Following this, 22% of literature was based in the continent of North America. Very few studies were undertaken in Africa, Australia and Oceania or South America (2%, 2% and 1% respectively). Fig. 1c provides this data at the country level, where it was given, and indicates that most English language research was undertaken in the USA which has nearly twice the number of papers than the next highest publishing countries, China, UK, France and Germany. Many papers do not undertake research at the individual country or continent scale but take a global perspective, these have been labelled as 'World' in Fig. 1b and 1c, which provide examples of review or discussion papers.

The majority of papers (125) were those that had 'quantified' ES, while 32 were classed as 'discussion' papers and 21 were 'general urban soil' papers. In the discussion papers there was a focus on soil biological activity and C storage, however, most discussion papers (47%) mentioned numerous ES categories. Biomass provision for food and cultural services were poorly represented, with food being mentioned in two discussion papers, and cultural services mentioned in only one.

3.1.2. Specific ES analysis

To provide an understanding of which individual ESs had been studied, an analysis of specific ESs was undertaken on the 125 papers that had 'quantified' data, as illustrated in Fig. 2. A majority (88%) of these quantified studies focused on supporting processes, with 42% of the studies measuring soil biological activity, 34% measuring nutrient cycling and 12% measuring water cycling. The predominance of studies focusing on these supporting processes, particularly nutrient cycling and soil biological activity, highlights their importance in understanding soil functioning and their support in providing ESs. However, there appears to be less of a focus on water cycling as a supporting process in urban soils. This may be because urban soil water dynamics are commonly studied in relation to water storage capacity or urban water management, and therefore these papers will be captured within the regulating service of flood mitigation.

Regulating ESs were also frequently studied in the quantitative literature (71% of studies), with 30% measuring C storage and regulation of greenhouse gases (GHG), and 21% measuring the recycling of wastes and detoxification. Flood mitigation appeared in only 9% of quantified papers, with only a small number measuring urban stormwater management as an ES. This does not reflect the extent of research and practical experience within professions working on urban water and sustainable urban drainage systems (SuDS) (Ciria, 2013; Davis and Naumann, 2017; Schifman and Shuster, 2019). It does, however, suggest that stormwater management is commonly seen as a problem to rectify rather than framed as the soil ES of flood mitigation; and as such the knowledge developed in engineering and water disciplines may not be reaching the wider ES community. There was also a lack of studies on the regulating service of biological control of pests and diseases in urban soils.

Provisioning ESs were less often studied, with the service of food, wood and fibre provision making up only 3% of the quantified papers. This is in contrast to research in non-urban soils where food provision is often quantified as one of the most important soil ESs (Adhikari and Hartemink, 2016; Holt et al., 2016). Urban agriculture is a well-established practice across the world, represented by a broad range of literature (Orsini et al., 2013; Ackerman et al., 2014; Mok et al., 2014; Edmondson et al., 2020); however, our findings suggest it is rarely studied in the context of urban soil ESs, and may have been missed from the literature as it does not explicitly mention soil ESs. The later average publication date for food, wood and fibre provision studies (Fig. 2) may, however, suggest that it is a growing area for ES studies. Physical support for built infrastructure, such as roads or buildings, occupied only 2% of the quantified papers which does not reflect the communities of research and practice in urban soil geotechnics (Trombetta et al., 2014; Denies et al., 2015; Vardon, 2015; Price et al., 2018). This suggests that while well–established, engineering and geotechnical communities may

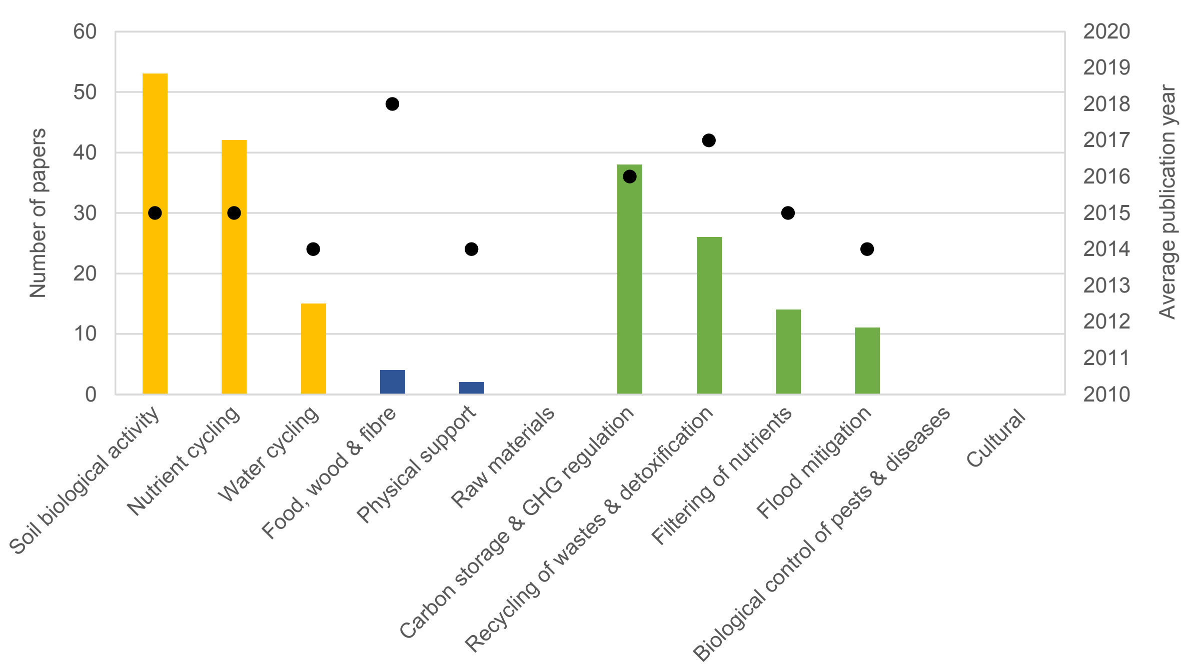

Fig. 2. Number of papers measuring supporting processes and ESs. Papers included are those that quantified ESs (number = 125). Yellow, blue and green columns represent supporting processes, provisioning and regulating ESs respectively. Circles indicate average (mean) publication year for each ES, shown on secondary axis.

not be considering urban soils within an ES framing. In addition, the literature search did not identify any studies on raw materials from urban soils, or on the concept of urban mining, the recovery and reuse of resources from waste materials (Arora et al., 2017).

None of the studies undertook survey or analytical work on cultural services from urban soils. There is a large body of work on the cultural and archaeological significance of soils capturing historical and societal information, referred to by some as cultural layers within cities (Burghardt, 1994; Vasenev and Kuzyakov, 2018). However, this work does not appear to use the terminology of ESs, perhaps because ES research has largely been developed by ecologists and economists rather than by heritage researchers (Hølleland et al., 2017). In addition, there is a growing body of evidence for the importance of access to nature and urban greenspaces for both mental and physical health benefits (Pretty et al., 2011; Lovell et al., 2018; Chen et al., 2019); however, these benefits are often captured in relation to trees or urban forests rather than soils. The approach to studying cultural ESs remains an on–going debate (Fish et al., 2016), and as such, their study in both urban and non-urban soils is still relatively rare.

Across all individual ESs quantified, the greatest number of studies were undertaken in the USA, followed by China and European countries. After the USA, a relatively large proportion of the soil biological activity studies were undertaken in France; while for C storage, numerous studies were completed in the USA, UK and China. A small portion of the quantitative literature (6%) focused on Technosols, defined as soils dominated by technical human activity and evidenced by a substantial presence of artefacts or an impermeable constructed geomembrane (Rossiter, 2007). These papers focused mostly on constructed Technosols and their effects on soil biological activity, water infiltration and nutrient cycling, and were almost exclusively undertaken in France.

3.1.3. Interrelation between ESs studied

Most papers (57%) studied only one ES, while 26% studied two services, 15% studied three, 2% studied four and only 1% studied five. Where more than one service was studied, common pairings of services were quantified together which illustrated the interrelation between them. There was a predominance of supporting processes being studied together, for example, 48% of nutrient cycling papers also measured soil biological activity, two processes that are particularly intertwined (Bardgett, 2005); and 47% of water cycling papers also measured nutrient cycling, highlighting these measures as important indicators for urban soil functioning.

Instances of regulating services studied together were less common, for example, there were only four papers where flood mitigation was studied alongside C storage. Only two papers studied filtering of nutrients alongside recycling of waste and detoxification, suggesting the link is not being made between the pools of contaminants and the ability of soil to filter these or prevent their release into the environment.

The interrelation between supporting processes and regulating or provisioning ESs varied. Of the papers that measured C storage, 39% also measured nutrient cycling; while only 21% measured soil biological activity, suggesting only a small number of papers are making the connection between soil biota and C storage in urban soils. Water cycling was not commonly measured with flood mitigation suggesting these services are thought of separately and by different groups of researchers. In addition, nutrient cycling was rarely measured alongside food provision, which again suggests different groups of researchers or practitioners each with their own terminology and data collection methods.

The lack of interrelation across service types highlights that supporting processes and ESs are not commonly considered together; and that regulating services are not often studied together or with provisioning services. This lack of studies on multiple ESs illustrates that the opportunity to quantify the multifunctionality of soil is being missed. There is a need to measure supporting processes to understand the basis of ES provision, but there is also a need to quantify regulating and provisioning services together to allow the multifunctionality of soil to be included in urban planning and decision making.

3.1.4. Depth of urban soil studied

Data on the maximum depth and number of measurements down the soil profile was gathered from the literature, where it was provided (Fig. 3). Of the 104 papers that gave depth information, the majority of papers studied soil between 0 and 20 cm (63%), while 14% studied down to 40 cm, and 12% studied down to 100 cm. Papers studying deeper than 100 cm (5%) were restricted to those that used deep cores to study subsoil drainage (Herrmann et al., 2017), lysimeters to observe leachate (Yilmaz et al., 2019; Cannavo et al., 2018), soil chemistry under sealed surfaces (Kida and Kawahigashi, 2015), and risks associated with soil swelling (Vallone et al., 2008). Most papers studied just one soil depth (70%) while a smaller number of papers investigated differences between two, three or more than three depths (10%, 15% and 5% respectively).

3.1.5. Co-occurrence analysis of key terms

An analysis of the co-occurrence of key terms in the literature led to a network visualisation of the terms and links between them. Three clusters of terms are identified, highlighted by colour in Fig. 4, with clusters representing similar observations or processes occurring together in the literature.

Within the C and nutrients cluster (blue) there is a focus on stocks of C and nutrients and the impacts of urban land cover on their storage, such as soils under buildings or impervious surfaces, or different vegetation types such as urban forests or lawns. The soil biodiversity cluster (green) highlights a separate group that focuses on the abundance and diversity of species, their distribution across different green infrastructure types, their activities such as nutrient cycling, and the consequences of urbanisation and disturbance on them. Finally, there is a third cluster focused on the challenge of urban soils (purple), which includes the impacts of urbanisation, risks to soil such as soil sealing, excess runoff and contamination, opportunities to manage and plan to protect urban soil better, and strategies to highlight its importance in planning documents.

The clusters of key terms reflect what is shown in the specific ESs analysis (section 3.1.2), that research tends to focus on supporting processes with a predominance on soil biological activity, as well as soil C and nutrient stocks. There is an area of cross over between the blue and green clusters where terms represent a range of green infrastructure types that have been studied such as urban parks, lawns and different vegetation types. These terms co-occur together and are relevant for both the C and nutrient cluster and the soil biodiversity cluster. This aligns with patterns found in the ES literature analysis (Fig. 2), which showed that most studies focused on soil biological activity, nutrient cycling and C storage.

There is a distinct lack of terms associated with water across the co-occurrence analysis, be that flooding, water holding or water cycling, and while the terms soil sealing and impervious surface are included, they are not connected to issues of flooding. However, the ESs literature analysis (section 3.1.2) illustrates a small but important number of studies that investigate water cycling, runoff and flood mitigation. These studies use a range of measurements of soil water such as percolation, infiltration, water holding, runoff, saturated / unsaturated hydraulic conductivity and field capacity, and therefore, it is possible that these terms do not appear frequently enough in the literature to be captured in the co-occurrence analysis.

Another notable gap in key terms are those that relate to food and urban growing which correlates with the lack of literature on food provision in the ES literature analysis, reiterating the lack of food provision terminology used in the urban soil ES community. Likewise, cultural services were also not represented within the co-occurrence analysis, representing the lack of studies found in the ES literature.

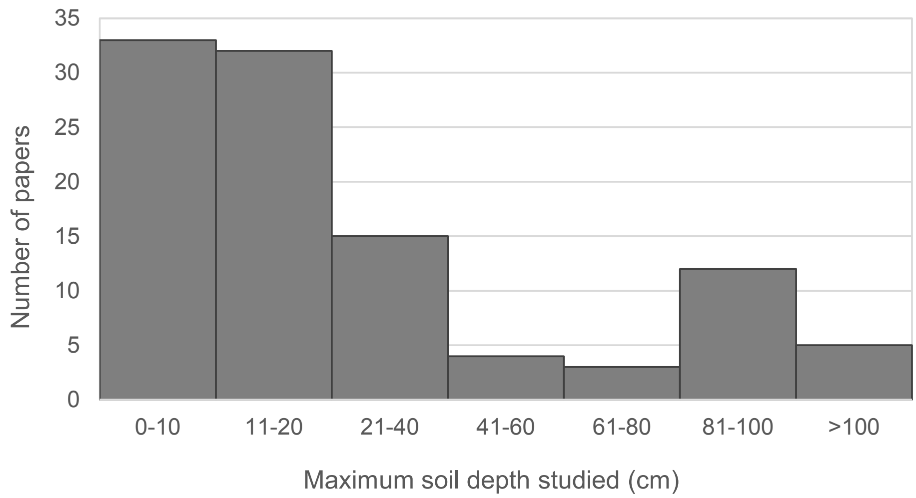

Fig. 3. Maximum depth (cm) at which papers studied urban soil ESs.

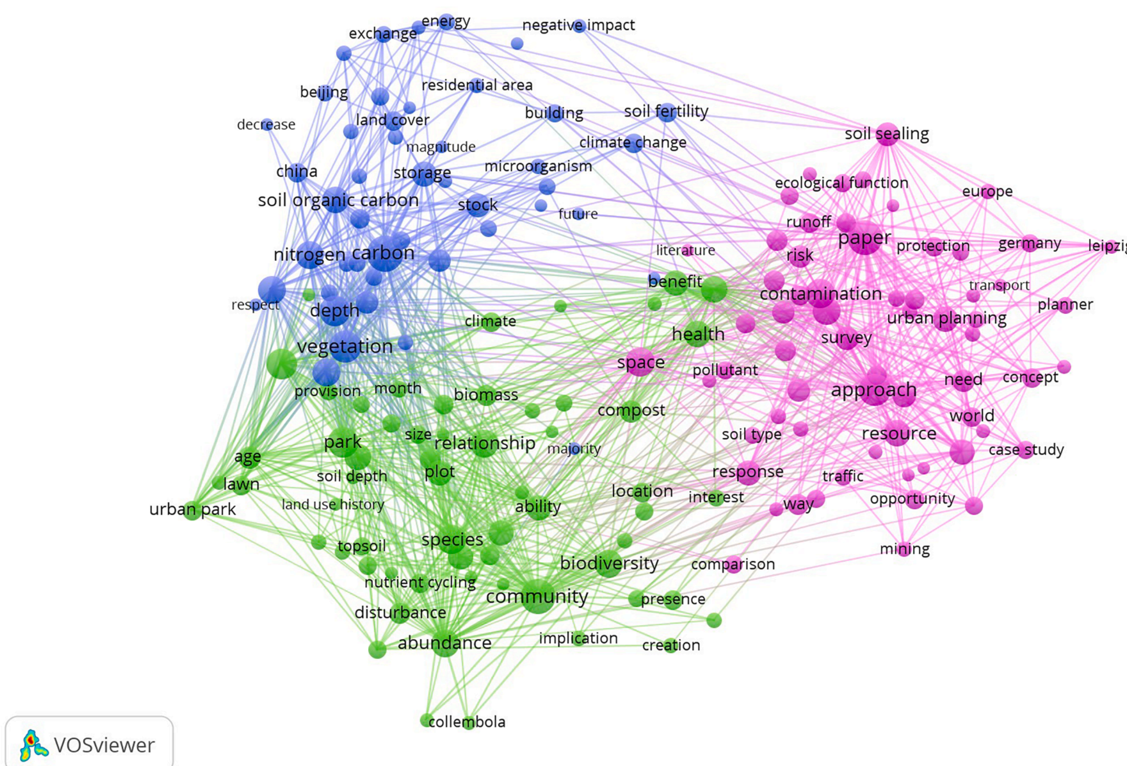

Fig. 4. Co-occurrence analysis of key terms within the urban soil ecosystem service literature. Nodes represent terms that occur at least five times, with the size of node denoting the number of occurrences. Vertices and relative distance of nodes illustrate the co-occurrence of terms. Three clusters where the interconnections of terms are strongest are identified, denoted by colour: C and nutrients (blue); soil biodiversity (green); and the challenge of urban soils (purple).

3.2. Summary review of urban soil ESs

Having analysed which urban soil ESs have been quantified, where this was undertaken and the nature of the research community in 3.1, here we provide an overview of research reported in the 'quantified' literature identified by ES category. We prioritise primary research studies in order to provide some insight into what is known and where future research gaps may lie.

3.2.1. Supporting processes

3.2.1.1. Nutrient cycling. Human activities and land use have the potential to alter nutrient cycling in urban soils due to direct and indirect additions and removals of nutrients, and modifications to factors affecting nutrient cycling.

Several studies have found that soils under some urban land uses can have high nutrient contents. Schindelbeck et al. (2008) compared land use in New York state and Baltimore, finding that soils from a recreational park and brownfield plot had higher organic matter content and mineralizable nitrogen (N) content than soil from a non-urban vegetable farm. In Lahti (Finland), soil in a managed garden site showed consistently higher nutrient content compared with human-made soil on a landfill site (Vauramo and Setala, 2010). In Leicester (UK), allotment soils had higher amounts of organic N than soils from surrounding intensive arable fields, which was attributed to additions of compost or manure (Edmondson et al., 2014a). The time period over which the soil has been under a particular land use is also an important determinant of nutrient status. Soil organic matter and nutrient contents have been found to correlate with park age (Setala et al., 2016) and housing age (Cobley et al., 2018) in studies in Finland and the USA respectively.

Conversely, some urban land uses and conditions led to a reduction in nutrient contents. For example, Herrmann et al. (2017) found that imported soil, used to fill excavations on previously developed land, showed less nutrient support for plant growth with lower N levels than pre-existing soils at the site. Nutrients have also been found to be depleted in areas where an accumulation of heavy metals was apparent (Zhao et al., 2013).

Phosphorus has been studied significantly less compared to other macronutrients in urban soils; however, it is likely that it would be equally altered by urbanisation through physical modifications such as land use, vegetation types in greenspaces (Setala et al., 2017), human or industrial waste additions (Yang and Zhang, 2015), and altered soil biology such as earthworm activity (Amosse et al., 2015). Likewise, there were few studies that considered other physical modifications to the urban environment and their effects on nutrient cycling, for example, connections were not commonly made between altered urban hydrology, microclimate, aeration and soil structure and how these might affect urban soil nutrient cycling.

3.2.1.2. Water cycling. The primary factors influencing water cycling in urban areas are the extent of impermeable surfaces, soil infiltration capability and drainage, and evapotranspiration (McGrane, 2016). However, other factors also contribute to altered soil water cycling, including the heterogeneity of urban soil, greenspace management, altered horizons and compaction due to construction activities.

A number of studies identified by the literature focused on infiltration, soil moisture dynamics and water holding. One of the earliest papers identified mapped infiltration rates for Hannover (Germany), including areas covered by roads and buildings as well as open soils and vegetation covered areas (Bartsch et al., 1997). In a modelling study in Leipzig, Haase (2009) found that water cycling had accelerated due to increased sealing with impervious surfaces, leading to reduced water holding capacity in favour of increased runoff. Recent modelling studies have considered soil moisture dynamics across different world cities with varying levels of permeable surfaces (Revelli and Porporato, 2018), as well as the effects of developments on groundwater recharge and the sensitivity of this to future climate scenarios (Manna et al., 2017).

The link between organic matter and soil water holding, as observed in traditional soil science (Rawls et al., 2003; Minasny and McBratney, 2018), has also been observed in the urban soil literature. A recreational park soil in New York state had higher available water capacity compared with farm or brownfield soils, attributed to the high organic matter content (Schindelbeck et al., 2008); while Oldfield et al. (2014) found that compost additions to soil led to increased water holding capacity in the New York City Afforestation project. In urban gardens in Zurich, Tresch et al. (2019a) found high correlations between C mineralisation and water holding capacity as part of a study on soil multifunctionality. They found that soil moisture and disturbance, driven by watering and tilling, were key drivers in structuring plant and soil fauna communities, which in turn influence multifunctionality, thus highlighting the importance of watering regimes in soil multifunctionality.

While extensive methods are used to measure natural and agricultural soil physical and hydrological properties, measurements of infiltration in urban soil present unique challenges due to the presence of artefacts (Rhea et al., 2014). There are a limited number of studies into the properties of Technosols in relation to water cycling, and methods to investigate hydraulic properties of several Technosols were compared by Yilmaz et al. (2019); while soil water in Technosols made with waste were studied by Cannavo et al. (2018) who found that physical properties were not necessarily a limitation to tree growth.

3.2.1.3. Soil biological activity. A recent review by Guilland et al. (2018) found that studies on the biology of urban soils made up around 2–3% of all studies of soil biology. Whilst this is in line with the extent of urban land cover globally, arguably a greater focus on urban soils is needed as there is a clear relationship between biodiversity, ecological processes and ES provision (Mace et al., 2012), and this is closely linked to the location of the majority of the population. Guilland et al. (2018) found that most studies were about microorganisms, nematodes and arthropods (33%, 28% and 21% respectively), and that most studies focused on ecotoxicology or bioaccumulation of contaminants rather than the ecological and functional aspects of soil biological communities.

Contrary to assumptions, soils in urban areas do not always have compromised soil fauna. Based on a study of microarthropod biodiversity, urban soils may provide the same level of biological quality as forests (Joimel et al., 2017); and while not picked up in the ES literature, Ramirez et al. (2014) found that the breadth of microbial diversity in Central Park in New York was similar to microbial diversity across the world. Direct comparisons of urban to non-urban soils can, however, lead to varying conclusions, as urban land uses studies in China and Finland have found lower soil microbial biomass than in natural forests (Zhao et al., 2013; Francini et al., 2018); whereas microbial activities of urban soils in Stuttgart were comparable to agricultural or forests soils (Lorenz and Kandeler, 2006).

A variety of factors have been found to influence soil fauna distribution within urban areas (Santorufo et al., 2014; Xie et al., 2018; Joimel et al., 2019; Tresch et al., 2019b). Soil parameters were found to exert a stronger influence on soil fauna than plant communities in vegetable gardens (Joimel et al., 2019); however, Tresch et al. (2019b) found that plant species richness affected soil fauna diversity and microbial activity in urban gardens. It has also been observed that the typical pattern of plant–microbe associations seen in non-urban soils has also been seen in urban soil, such that urban soil bacterial and fungal communities can respond to plant functional groups (Hui et al., 2017). Nevertheless, there remains limited understanding of what influences microbes' distribution in urban soils (Wang et al., 2018).

Urban land use can also have an effect on soil fauna. Urban soils have been observed to exhibit greater functional diversity than other non-urban land uses, particularly in roadside tree soils in Beijing (Zhao et al., 2013); and greater species diversity in park and roadside soils compared to residential soils in Chicago (Wang et al., 2018). The history of disturbance also has an influence, as the relationship between soil biota and physicochemical variables can vary with soil age (Amosse et al., 2016); and park age can shape composition of microbial communities (Hui et al., 2017).

Microbial activity can be affected by pollutants such as heavy metals and pesticides (Gan and Wickings, 2017). For example, Ivashchenko et al. (2019) found microbial C-availability and organic matter decomposition were lower in industrial and residential zones of Moscow where there were higher levels of heavy metals, and metal contaminated soils have also been shown to have lower levels of nitrifying bacteria and a lack of fungi (Hartley et al., 2008).

3.2.2. Regulating services

3.2.2.1. Flood mitigation. The ability of urban soils to provide flood mitigation is largely influenced by land use and land surface treatment (Haase, 2009; Wheater and Evans, 2009). Urban forest soils have been shown to have better drainage than soils on residential or commercial land (Dobbs et al., 2011), and have higher runoff regulation than other urban land uses (Ziter and Turner, 2018). The size of urban forest patch was not found to affect hydraulic conductivity in a study by Phillips et al. (2019), who conclude that the protection of urban forest patches, whether small or large, can potentially contribute to urban stormwater management.

Sealed land surfaces, such as impervious roads and paving, notably increase surface runoff. Runoff values start to double when impervious surfaces cover >20% of land, and a model for Leipzig has shown that runoff can reach over 75% of the annual precipitation level when areas are >80% impervious (Haase, 2009). A more recent study shows that runoff values could increase by >20% in highly sealed areas (Ungaro et al., 2014). Where permeable soils remain, for example around the base of street trees, there is an increase in rainfall infiltration (Revelli and Porporato, 2018). One possible solution to increased runoff is the use of suspended pavement systems, such as those above tree pits, which in a study in Knoxville (USA) reduced 99% of measured runoff volumes, and captured runoff from 79% of storms (Tirpak et al., 2019). Inclusion of soil sealing management in planning strategies and policies has also been considered to reduce the growth of sealed areas (Artmann, 2015, 2016).

The extent of human disturbance, compaction and addition of anthropogenic material to the soil itself also influences the capacity for flood mitigation. Imported fill soils used in construction are variable, depending on the material used, but some have been shown to have greater infiltration and drainage than pre-existing soils (Herrmann et al., 2017). Soils with compost mixed into the subsoil and tilled had twice the saturated hydraulic conductivity of undisturbed soils, and 6–11 times that of soils subjected to topsoil removal and subsoil compaction (Chen et al., 2014). This suggests that some treatments may have potential in aiding stormwater mitigation.

3.2.2.2. Filtering of nutrients. Soils can filter and retain numerous organic or inorganic compounds and solutes and prevent them from reaching water courses (Dominati et al., 2010). The ability of soil to act as a filter can be influenced by vegetation cover; however, only a small pool of studies has considered the link between vegetation and urban soil as a filter. Urban soils under tree canopies have been found to have higher C to N ratios than soils under grass due to the higher C to N ratio in tree litter, and thus, are more able to buffer localised N fertilisers or atmospheric N deposition (Livesley et al., 2016). In a study by Ziter and Turner (2018), urban soils in grasslands and open spaces were found to have the lowest available phosphorus (considered as a proxy for potential P runoff) compared with urban forests and developed land in Madison (USA).

In addition to plant influences, other forms of C in urban soil may contribute to water filtration. Black C accumulation in urban soils may act as a sorbent of contaminants, and in combination with sufficient infiltration rates, may lead to improved water filtration and improved water quality in urban greenspaces (Schifman et al., 2018). A possible practice to improve soil filtration is the use of suspended pavement systems, as mentioned in section 3.2.2.1, on which a study has shown the concentration of influent suspended solids to be significantly reduced, demonstrating the bioretention potential of these systems to remove pollutants from urban runoff (Tirpak et al., 2019).

Urban soils can, however, act as a source of nutrients or pollutants when the soil's ability to filter them is compromised, and thus, the retention of pollutants can become an ecosystem disservice. Road salt can leach from urban soils into water courses, with riverine Cl- loading downstream of Calgary (Canada) attributed to increasing inputs of road salt (Kerr, 2017). Remediation of degraded urban soils often involves additions of compost that can lead to excess nutrient leaching and impacts on urban water quality. In a degraded urban soil experiment, N and P losses were considerable prior to vegetation establishment; however, once vegetation was established, N and P losses reduced to background levels (Basta et al., 2016). To reduce leaching risks, Heyman et al. (2019) identified a range of acceptable compost characteristics that would be beneficial for soil remediation without causing nutrient leaching. As with other land covers, plant type as well as litter inputs and the ratio of soil bacteria to fungi can also influence nutrient leaching. For example, urban soils with labile litter inputs and greater associated soil bacteria have been shown to leach more inorganic N than soils under recalcitrant, less readily decomposable litter, which have greater associated soil fungi (Vauramo and Setala, 2010).

3.2.2.3. Recycling of wastes and toxins. Soil has the ability to degrade and decompose some waste and chemical contaminants; however, if levels are high and the soil holds onto large amounts, it can represent a source of contamination to people living in cities. Thus, contamination, in particular that of heavy metals, has driven much traditional research on urban soils due to the risks posed to human health (Bullock and Gregory, 2009; Li et al., 2018).

Li et al. (2018) reviewed the range of organic and inorganic pollutants in urban soils and linked these to risks to human health. Studies highlighted by the literature search include those focused on heavy metals (Trammell et al., 2011; McClintock, 2015; Bretzel et al., 2016; Setala et al., 2017); polycyclic aromatic hydrocarbons (PAHs) (Lorenz et al., 2006; Monserie et al., 2009); salts used for road de-icing (Bouraoui et al., 2019); and anthropogenic residues, including traces of actinolite and chrysotile, types of asbestos (Kopel et al., 2016), which further contribute to human health risks.

These studies highlight contaminants present in urban soils, and that reducing public exposure to contamination is crucial. However, they do not typically frame the recycling, degradation and storage of contaminants as an ES provided by urban soil. Thus, while we know the levels at which substances become dangerous to human health, we do not necessarily study the soil's ability to recycle them, store them, and prevent them from being available for human exposure. A small number of studies addressed this, for example, Wang et al. (2015) showed that soil's natural attenuation capacity has strong potential to retain contaminants in urban areas and prevent public exposure; however, attenuation capacity is impacted by urban land use and the extent of soil sealing. More broadly, there is a need to highlight where urban soils are providing this service, protecting humans from exposure, or conversely where the service is compromised, provides a disservice, and urban soils pose a risk.

3.2.2.4. Carbon storage and GHG regulation. A recent review by Vasenev and Kuzyakov (2018) found that urban soil C content may be higher than in natural soils, and combined with C accumulation through the soil profile to 100 cm, resulted in total C stocks 3–5 times greater in urban soils than natural soils. Across all climates and city sizes, residential areas showed the highest soil organic carbon (SOC) stocks while industrial zones and roadsides showed the highest inorganic C and black C stocks (Vasenev and Kuzyakov, 2018).

Studies identified by the literature search illustrate a comparison between urban and non-urban soils for C storage. Urban park soils in Milan were found to have higher SOC stocks (0–40 cm) compared with croplands in the region, and comparable SOC stocks to other non-urban soils of the region (Canedoli et al., 2020). An analysis of Leicester (UK), including both vegetation and soils, found that urban SOC storage was significantly greater than in surrounding agricultural soils, and that 82% of the city's overall organic C budget was stored in urban soils (Edmondson et al., 2012). However, in Harbin city (China), urban SOC stocks (0–20 cm) were lower than local natural forests (Lv et al., 2016).

Within cities, urban land cover and vegetation type can influence urban soil C. Residential gardens and open spaces were found to have the highest total C stock (0–25 cm) in Madison (USA) by Ziter and Turner (2018) who note the legacy effects of historical land uses on urban soils. In Leicester (UK), residential garden soil had higher SOC concentration than soil in public greenspaces (Edmondson et al., 2014b). Urban soil under trees has been shown to have higher soil C stock (0–30 cm) than soil under grass (Livesley et al., 2016); while Edmondson et al. (2014c) found that SOC enhancement was related to tree species, with SOC being lower under mixed woodland. Urban soil C storage may also be affected by the type of plant litter inputs, for example, greater soil C retention has been suggested as a result of slower decomposition under plants producing recalcitrant litter, such as *Picea abies* and *Calluna vulgaris*, compared to labile litter (Vauramo and Setala, 2011; Setala et al., 2016).

A consistent pattern between urbanisation and soil C has not been found. In Singapore roadsides, SOC was inversely related to urbanisation (Ghosh et al., 2016); while in gardens in Zurich it was found to be positively correlated with urbanisation density (Tresch et al., 2018). A notable impact of urbanisation is soil sealing, and while studies into sealed soil are limited, some illustrate that soil sealing reduces SOC (Wei et al., 2013, 2014). However, Edmondson et al. (2012) found no difference in SOC storage between greenspace soils and sealed soils at equivalent depths; and Vasenev and Kuzyakov (2018) note that cultural layers and buried horizons can contribute to sealed soil C stores being isolated but not depleted.

Anthropogenic additions and imported fill materials can contribute varying levels of C to soils. For example, Herrmann et al. (2017) found imported fill soils had lower total C content than pre-existing soils, with large variability in the data. Engineering of urban soils has been considered to capture and store soil C using demolition materials. These can be rich in calcium and magnesium which capture atmospheric C through weathering and secondary carbonate mineral precipitation (Washbourne et al., 2012). In addition, black C, arising from incomplete combustion of fossil fuels, can accumulate in urban soil and is considered highly stable, and thus represents an important pool of soil C with long residence times (Canedoli et al., 2020).

Only two of the 125 'quantified' papers measured GHG emissions. The New York City Afforestation Project recorded higher N_2O emissions where shrubs and compost were not incorporated prior to tree planting, highlighting that plant and microbial uptake of inorganic N is important in regulating N_2O losses from urban soils (Pierre et al., 2016). In urban lawns in Melbourne it was found that reducing irrigation and fertiliser helped mitigate GHG emissions in garden systems, however, this needs testing in other soil types and environmental conditions (Livesley et al., 2010).

3.2.3. Provisioning services

There was a notable lack of studies on provisioning services, particularly on food production, which is in contrast with most non-urban soil ES literature. As discussed in section 3.1.2, urban food is a developed research area but was not studied specifically as an urban soil ES. This may be related to the common practice of importing materials used for urban food growing, such as compost or topsoil, thus giving the native soil less importance and consideration. Observations of food production were linked more to other services such as wellbeing or biodiversity, rather than solely quantifying the food itself. For example, in a study where radish *Raphanus sativus* were grown, the size of the food growing areas was shown to lack a correlation with the abundance and diversity of invertebrates, suggesting that even small food production sites can still provide ESs related to invertebrates (Biffi et al., 2019). Soil contamination can present a health risk from exposure, either from eating food grown in contaminated soil or from gardening and skin exposure to the soil. Issues around this can be low levels of concern and inconsistent knowledge of gardeners, barriers to conducting soil tests, and limited knowledge of best practice to reduce exposure (Kim et al., 2014).

Only two papers in the literature search considered the physical support of urban soils as an ES, highlighting the hazards of urban soils with poor mechanical properties (Vallone et al., 2008) and risks associated with swelling soils and damage caused to infrastructure, urging the inclusion of soil functionality in urban development (Stell et al., 2019).

3.3. Directions for future urban soil ES research

The preceding literature analysis and summary highlight several gaps in knowledge and needs for future research. Here, we summarise a number of research gaps identified and discuss opportunities for future work and collaboration to enhance urban soil ES.

3.3.1. Urban soil multifunctionality and trade-offs

Urban areas exhibit high heterogeneity, and potential ES providing areas are required to provide for many and diverse users (Gómez-Baggethun et al., 2013). Enhancing urban soil ES provision is dependent upon the requirements of beneficiaries of those services, as well as the management and treatment of the soil. Nonetheless, given the high density of people living in urban areas and wide range of urban soil ESs it is clear that multifunctionality is key; yet this analysis highlights that within the literature researched (section 3.1.3), only two papers studied four urban soil ESs together (Tresch et al., 2018; Montgomery et al., 2016) and one studied five (Míguez et al., 2020).

To deliver multifunctionality and management win-wins it is necessary to deepen and integrate our understanding of urban soil ESs across disciplines and professions. Opportunities for this could arise though increased study of multiple functions and the inclusion of soil multifunctionality in planning and green infrastructure policy (Scott et al., 2018). These policies could strengthen the protection of existing, and provision of new, urban greenspaces that take account of multiple soil ESs. They could also encourage the protection of existing, and creation of new, urban woodland that aids runoff and stormwater regulation (Ziter and Turner, 2018; Phillips et al., 2019) and soil C storage (Edmondson et al., 2014b, 2014c; Setala et al., 2016). Integration of soil ESs into masterplanning and infrastructure projects is necessary to enhance ESs and reduce disturbance to soil functions. Landscape design that enables multiple functions would incorporate diverse vegetation across greenspaces, encouraging a range of microbial and fungal communities and the soil processes they provide (Hui et al., 2017; Tresch et al., 2019b). Management of urban greenspaces also plays a key role, through maintenance schedules and increasing organic matter to enable soil to perform numerous functions (Lorenz and Lal, 2015; Setala et al., 2017). Win-wins may arise through practices such as SuDs to enable water storage, reduce runoff and capture and filter pollutants; or the use of suspended pavement systems and new developments in tree pit design to enable greater water flow whilst also providing bioretention (Tirpak et al., 2019).

However, as urban environments present such complexity, there will be decisions about trade-offs that need to be made. In contaminated soils there may be a choice between the mobility and leaching of contaminants or excess nutrients and improving drainage and infiltration. Choices of vegetation type can influence soil properties and, therefore, urban greenspace planting can influence outcomes for soil functions and service delivery. While these choices have been considered in studies in specific contexts, there remains a gap in clarity over best practice for urban greenspace management and landscape design for the provision of multiple ESs and consideration of trade-offs according to ES requirements for different contexts.

3.3.2. Gaps and opportunities

Beyond multifunctionality, which we identify as an overarching gap, the systematic review allows us to identify six further areas which we believe are key gaps and opportunities for future research.

1) **Water** – whilst much work exists on SuDs and stormwater dynamics, it does not appear to be connected with the ES community. It is vital that urban soil water dynamics are recognised within ES assessments and in considering the benefits of urban green infrastructure. Connections between soil water researchers, SuDs practitioners and the ES community need to be strengthened to enable this important work to be shared. It is also necessary to consider the impacts of soil

sealing, compaction and climate change on urban water dynamics for the future.

2) **Food** – interest is increasing in urban agriculture and it is essential that it is connected with the urban soil ES community to ensure the wider benefits of urban soil are known. This will allow consideration of the environmental and social benefits of urban agriculture, as well as risks associated with contamination. It will also enable food growing to be quantified and captured more holistically, and key messages to reach urban planners and policy makers.
3) **Cultural** – in securing these services for the future, it is vital that we capture the importance of urban soils for the range of cultural services it provides, whether through supporting provision of greenspaces for improved mental and physical heath, well-being through food growing, providing aesthetic or spiritual inspiration and sense of place, or through interpreting the layers of history that soil preserves through archaeology. It is especially necessary to take a holistic view of the variety of cultural and wellbeing services that urban soils provide, particularly as urban populations continue to grow, and to take them into account when considering benefits to people.
4) **Global research** – much of the current work is focused on the USA, China or Western European countries. There is a need for research to expand into other global regions, such as Africa, South America and Australia and Oceania, to consider the impacts of urbanisation on soils in a range of climates and in different urban contexts. This is particularly important with increasing pressures on land as cities grow rapidly across the world.
5) **Interconnection between researchers and policy** – there is a need to share quantification methods and findings across research disciplines and communities to enable the vast complexity of ES research to be shared and taken up by practitioners and policy makers. It is important that researchers work together and consider the impact of language and terminology on the uptake of research methods and findings, particularly in relation to planning and policy. This will also aid the study of multiple services and enable the uptake of methods by wider groups, NGOs, businesses and organisations.
6) **Drivers of change** – future drivers such as soil sealing, climate change, and the use of Technosols need to be considered to allow us to gain insight into how urban ecosystems will function as these drivers exert increasing influence. There is also a need to take into account how ESs may be affected by the combined effects of these drivers of change.

4. Conclusions

Research into urban soil ESs is a new but growing body of work and is providing much needed information on how urban soils function within the complex, heterogeneous contexts of cities. Most of the research focuses on supporting processes and selected regulating services, such as C storage and recycling of wastes. While the emphasis on supporting processes provides us with data to understand urban soil processes, it does not provide information that is easily used by those outside the soil science community and, thus, taken into urban planning and management. To address this, it is necessary for both supporting processes and ESs to be studied; and research into multifunctionality is highlighted as a key direction for the future. This would also address other gaps found in the literature, such as urban food growing, water dynamics and cultural services rarely being identified as services provided by urban soils. We hope that addressing these gaps will enable urban soils to be better understood and accounted for in the planning, design and management of urban areas in order to support future human wellbeing and urban ecosystem health.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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