Chapter 1
Urban Ecosystems: Soils and the Rise and Fall of Cities

Andrew W. Rate

Abstract Soils, as a crucial component of the critical zone of the Earth's surface that sustains life on land, are as essential in cities and peri-urban areas as they are in natural or agricultural environments. In this chapter we explore the idea that the properties and geographical location of soils have influenced the historical and present location of urban environments. The importance of cities to human survival and well-being is established by analysing global trends in urbanisation and urban migration and by noting that urban areas will become increasingly important for food production. The remainder of this introductory chapter presents the main topics which are covered in this textbook. Human impacts on urban soils are described in several ways, through an investigation of soil-forming factors in urban environments (Chap. 2), soil variability and data analysis (Chap. 3), ecosystem functions provided by soils (Chap. 4), changes in soil physical properties (Chap. 5), chemical pollution of soils (Chaps. 6 and 7), and soil biological phenomena in urban soil (Chap. 8). We start to consider the management of soils in urban environments in Chap. 9, which covers urban soils as a source and sink for material and some basics of risk analysis. The management theme is continued in Chap. 10 which analyses the role of soils in sustaining human health within the framework of the United Nations' Sustainable Development Goals and in Chap. 11 which presents remediation options for degraded urban soils. Finally, Chap. 12 looks to the future of soil science in an urban context.

Keywords Urban soils · Soils · Urbanisation · Population · Human impact · Ecosystem functions

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What you could learn from this chapter:

- Whether you want to keep reading this textbook!
- How soils and urban ecosystems are interlinked, in both the past and the present.
- The context and relevance of urbanisation of human populations.
- Why urban soils are important, and how they are different from 'other' soils (and therefore worth studying).

1.1 Introduction

Soils are the living core of the *critical zone*, the zone encompassing the upper layers of Earth's land surface which are responsible for sustaining terrestrial life. As much in cities as in land used for food production, forests, or pristine reserves, the properties and functions of soil are crucial for human survival and, indeed, for the healthy functioning of all terrestrial ecosystems. The critical zone is comprised of components of the near-surface environment, from the lowest accessible groundwater to the upper vegetation canopy, in which complex interactions involving rock, soil, water, air, and living organisms provide essential ecosystem services (National Research Council et al. 2001; Brantley et al. 2006). Even despite issues like pollution, surface sealing, and other consequences of mistreatment of urban soils, soils in cities remain both mundane and mysterious, delicate but degraded, and ignored yet indispensable.

It may also be in cities, however, that soils are, paradoxically, least understood. For example, there is some evidence that the general population (including regulators, legislators and planners) makes very little use of soil knowledge (Teixeira da Silva et al. 2018). A proportion of the urban population, though, has close contact with and both personal and financial investment in urban soils; in urban and *peri-urban* environments, gardeners and urban farmers have a detailed knowledge of urban soils (Wakefield et al. 2007; Reséndiz-Paz et al. 2013). Many scientists and engineers also understand urban soils; in order to rehabilitate natural environments, clean up pollution, prevent erosion, and of course build on or using soil, a thorough understanding of soil properties and functions in an urban context is needed. The following passage from McDonald et al. (2019) expresses the impacts of urbanisation on biodiversity (and, therefore, humanity) very compellingly:

> By 2030, an additional 1.2 billion people are forecast in urban areas globally. We review the scientific literature (n = 922 studies) to assess direct and indirect impacts of urban growth on habitat and biodiversity. Direct impacts are cumulatively substantial, with 290,000 km^2 of natural habitat forecast to be converted to urban land uses between 2000 and 2030. Studies of direct impact are disproportionately from high-income countries. Indirect urban impacts on biodiversity, such as food consumption, affect a greater area than direct impacts, but comparatively few studies (34%) have quantified urban indirect impacts on biodiversity. (From the Abstract in McDonald et al. 2019)

At this stage in this book, we need to define what we mean by 'urban'. For this definition we are guided by the analysis presented by Liu et al. (2014), who discussed definitions of urbanisation in the context of how much of Earth's land area is occupied by cities. We will use the definition of 'urban' in the widest context described by Liu et al. (2014) that of land (and therefore soil) within the administrative boundaries of cities, which encompasses nearly 3% of global land area. In many cases, this definition extends to peri-urban or even rural land as well, which is appropriate for our purposes. Most of our examples will be drawn from built-up urban land closer to city centres, but in some cases of industrial or even degraded rural land, it makes more sense to use the wider definition. Sometimes industrial activities, which have many similar effects on soils as cities, occur in rural areas. Similarly, sometimes historical cities have ceased to exist as built areas or centres of human population but still leave an imprint on the properties and composition of the soil.

1.2 The Influence of Soils on Cities

Urbanisation (the movement of human populations into cities) and soils have been linked phenomena for a very long time. Cities, and civilisations, arose following the development of agriculture in areas where there were both fertile soils and accessible fresh water (McNeill and Winiwarter 2004; Hillel 2006), although several other factors were involved. Figure 1.1 expresses this graphically and lists several other factors including proximity to trade routes or topography and climate. From independent beginnings in places like Mesopotamia, China, and the Americas, the fertile land which was required to grow crops nourished a growing human population. The stability which agriculture – dependent on soil fertility – allowed was followed by the establishment of permanent settlements, which ultimately became towns and cities (Hillel 1991; Redman 2011). In today's world, the locations of contemporary cities, and the diverse range of urban environments, share much in common with the cities which developed millennia ago. Kummu et al. (2011), for instance, find that more than half of the world's population lives within 3 km of fresh surface water.

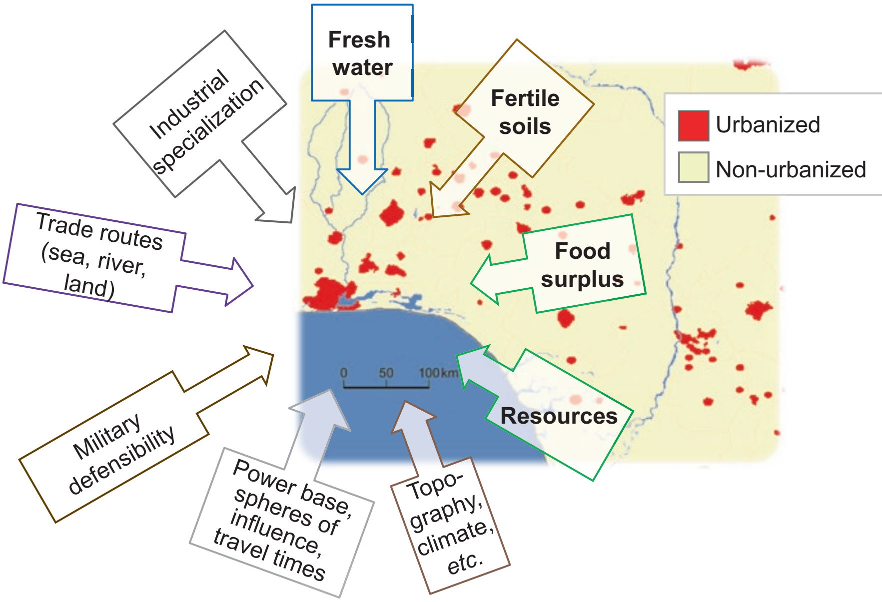

Fig. 1.1 Factors affecting the location of cities (bold text shows factors allowing the commencement of urbanisation). Graphic by Andrew W. Rate

The benefits of living close to fresh water are not restricted to water availability alone; as Fang et al. (2018) point out, rivers are associated with fertile soils and also provide transport routes and the conveniently low relief of alluvial plain environments, especially near the coast. Figure 1.2 shows the clustering of large, contemporary cities along coastlines, on major rivers, and especially in areas with fertile soils. In an ominous foreshadowing of contemporary environmental problems, even ancient cities, like the cities of the twenty-first century, contained polluted soils or soils which were degraded in other ways (Zhang et al. 2005). Urban environments are considered sufficiently different from other environments that some authors consider them as a separate Earth subsystem, the *urbosphere* (a term probably first used by Voloshyn 2004).

1.3 Global Trends in Urbanisation

Since approximately 2007, urban environments have been the most populous human habitat on Earth, a trend (Fig. 1.3) that is projected to increase the proportion of human population in urban areas until at least 2050 (Foley et al. 2005; Grimm et al. 2008; Lyons and Harmon 2012; United Nations 2018). The trend towards greatly increased urbanisation has been occurring steadily since about 1800 AD (Grimm et al. 2008) in many nations worldwide, with some countries (e.g. Brazil, much of

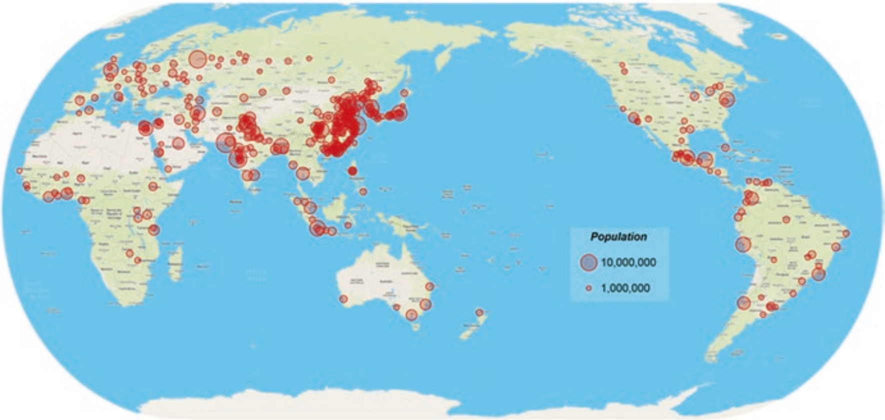

Fig. 1.2 World map showing locations of cities (red-coloured circles with area proportional to population) with population greater than one million inhabitants. (Robinson Conformal Projection using data from Mapbox (2019) and UNdata (2019); graphic by Andrew W. Rate)

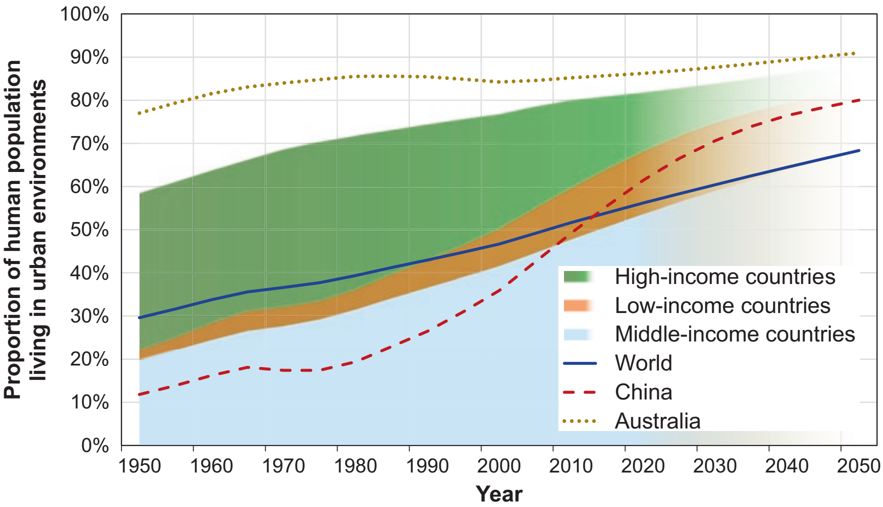

Fig. 1.3 Changes in the proportion of Earth's human population living in urban areas, 1950–2050. Data and projections from United Nations (2017, 2018); graphic by Andrew W. Rate

eastern Europe) showing their greatest urbanisation rates in the mid-twentieth century. The late twentieth century has also seen accelerations in urbanisation rates in several countries, including China, Indonesia, and South Korea (Luo et al. 2012; United Nations 2018). In contrast, countries such as Australia and the United Kingdom had already become highly urbanised by the beginning of the twentieth century, with low, stable rural populations and population growth only in urban areas. Some of the urban growth is manifested in the increasing sizes of cities;

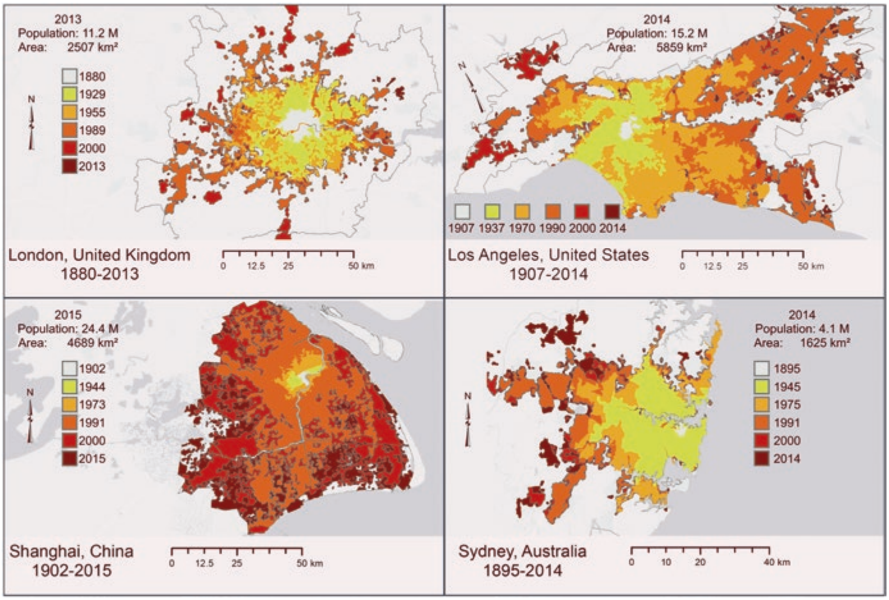

Fig. 1.4 Expansion of different urban areas showing the growth of four selected cities as a function of time (the darker the map shading, the more recently an area was converted to urban land use). The larger the relative area of darker-coloured shading, the more recent the expansion. Maps are compiled from Angel et al. (2016)

Fig. 1.4 shows growth in the geographic extent of some contrasting cities over the last approximately 200 years. The maps in Fig. 1.4 exemplify the rapid recent change in countries like China.

1.4 Human Use of Soils

The fertile soils that allowed cities to flourish also mean that urban areas are becoming increasingly important areas for food production (Satterthwaite et al. 2010). In 2000, about 6% of the world's croplands were in urban or peri-urban areas; the largest areas of land growing irrigated urban crops are in Southern and South East Asia, with mainly rain-fed urban crops grown in North America and Europe (Thebo et al. 2014) (Fig. 1.5). In many cities worldwide, the area of land dedicated to gardening in cities is increasing, with a resurgence in developed countries, with projects like urban community gardens providing not only a source of food but also health and social benefits (Wakefield et al. 2007; Laidlaw et al. 2018). As urban populations continue to increase, a greater proportion of food will need to be grown in urban or peri-urban areas (Thebo et al. 2014).

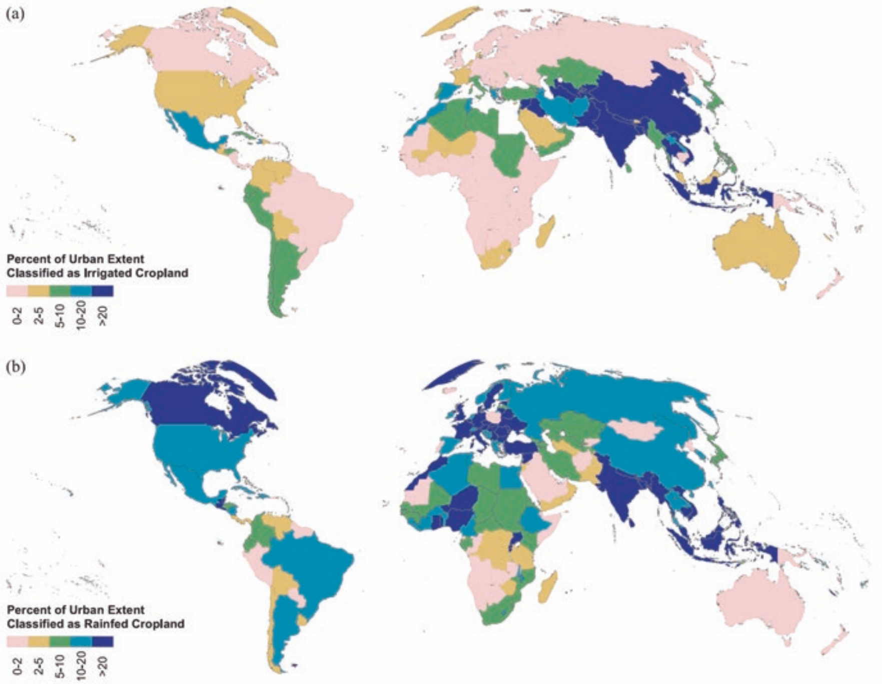

Fig. 1.5 Percentages of urban extent occupied by irrigated or non-irrigated cropland (recoloured from Thebo et al. (2014); used within the terms of a Creative Commons (CC BY 3.0) license)

Soils in cities are commonly much different from natural, unmodified soils, reflecting the importance of human factors in terms of their original *parent material* and soil-forming processes. The *geomorphology* of cities can also be highly modified, for example, by flattening of topography, redirection of streams and rivers, or drainage of wetlands (Alexandrovskaya and Alexandrovskiy 2000; Paul and Meyer 2001). Soils subject to a dominant human, or *anthropogenic* effect, are recognised explicitly in theories of soil formation (Amundson and Jenny 1991; Pouyat et al. 2008) and have been formalised into many of the widely used *soil classifications* (such as those presented in Isbell 1996; IUSS Working Group WRB 2014). Soils modified by humans may even provide a clear marker of the *Anthropocene*, the most recent geological period defined by profound human impact (Crutzen 2002). Certini and Scalenghe (2011) argue that the beginning of the Anthropocene is most appropriately and accurately marked by the presence of anthropogenic soils. These anthropogenic soils are called Anthroposols and Technosols in the United Nations' World Reference Base for Soil Resources (IUSS Working Group WRB 2014). Anthroposols are not confined to cities, nor are all urban soils Anthroposols or Technosols, but understanding anthropogenic soils is very instructive for understanding soils in urban environments. The formation and properties of urban soils, including Anthroposols and Technosols, will be covered in Chap. 2.

One of the most obvious differences between anthropogenic urban soils and their natural counterparts is that urban soils contain buried objects, or *artefacts*, derived from human habitation and management of urban environments. In some cases, these artefacts may be of archaeological significance and preserve valuable information about historical cultures (Alexandrovskaya and Alexandrovskiy 2000; Dubay 2012). Alternatively, the artefacts may simply be more recent additions of building rubble or other waste materials, engineered layers, or simply relocated soil material. In either case, soil conditions may result in *weathering* and loss of some anthropogenic signals (Howard and Olszewska 2011). Chapter 2 will also address the archaeological significance of urban soils and sediments.

Urban soils can be extremely heterogeneous, with steep gradients in soil properties observed over relatively small spatial scales (Schleuß et al. 1998; Rate 2018). This heterogeneity reflects the overprinting of natural soil-forming processes and parent materials with recent, and in some cases substantial, additions and losses of material caused by urbanisation, coupled with similarly recent changes in soil-forming factors such as vegetation and (micro)climate. Soil variability in any environment has implications for soil sampling and subsequent measurements and how soil data are analysed. Chapter 3 discusses the nature and implications of urban soil variability and presents some strategies for sampling and analysis of soils and statistical and numerical methods for exploration and interpretation of soil data.

1.5 Human Impacts on Soils

Numerous differences in *soil physical conditions* exist between urban and non-urban environments. Some of the most obvious of these are compaction, surface sealing, and changes in energy balance due to urban *heat island* effects. The physical properties of, and processes in, urban soils will be discussed in Chaps. 4 and 5, along with the implications of changes in soil physical conditions and geomorphology for urban hydrology (the behaviour of water in urban landscapes).

The human signature in urban soils may also be present as changes in the *chemical composition* of soils relative to their natural or ‘background’ state. These changes are *geochemical* records, separate from physical artefacts, which contain information on the history of urban land use (e.g. Zhang et al. 2005; Davidson et al. 2006; Albanese and Cicchella 2012; Appleton and Cave 2018; Rate 2018). The distinct chemical composition (i.e. a characteristic combination of concentrations of the chemical elements) or *geochemical signature* in geochemical records of urban soils can be interpreted with *spatial analysis* and *statistical analysis* of soil chemical composition, and we will address some of the issues involved with these analyses in following chapters. The changes in chemical composition of soils caused by urbanisation extend tens of kilometres to more than 100 km from urban centres, depending on the size of a city (Pouyat et al. 2008), and so represent a potentially powerful tool for understanding the effects of urbanisation on soils.

Changes in soil composition due to human activity, however, are often due to various forms of *pollution*. If substances are added to a soil (by pollution, or otherwise) in amounts or concentrations that are considered harmful to humans or other organisms, a soil is considered to be *contaminated* (National Environment Protection Council 2013). Soil contamination degrades the very resource(s) that originally made the cities possible and is an inherent consequence of the wide range of human activities that occur in urbanised areas. Chemical pollution in soils will be discussed in Chap. 6 (inorganic contaminants) and Chap. 7 (organic contaminants). Chapter 4 will also present essential concepts for understanding the chemical composition and reactions in soil systems, with a focus on processes encountered in urban soil environments.

Urban soils can provide the same *ecosystem services* and perform the same functions as non-urban soils, regardless of the multiple differences in the properties, starting materials, and formation processes (Sauerwein 2011; Lal and Stewart 2017; Teixeira da Silva et al. 2018). In reality, urban soils exist on a continuum between highly modified anthroposols and unaltered natural soils, and there is no clear boundary between them (De Kimpe and Morel 2000; Byrne 2007). In many cases their origins and *pedogenesis* (i.e. formation processes) are similar to 'natural' soils (Giusti 2013). The range of soil functions and ecosystem services provided by soils will be discussed, with emphasis on urban systems, in Chap. 4. In addition, since many important functions of soils are mediated by microorganisms and because microbial ecology is sensitive to changes in soil conditions, Chap. 8 expands on below-ground biological processes in soils and reviews the effects of urban soil changes on the abundance and diversity of soil organisms. Although we do not have a separate chapter relating to the influence of urban soils on above-ground vegetation (and nor is there a separate section or non-soil fauna), this discussion is integrated into several of the other chapters.

The pollution and subsequent soil contamination which are widespread in cities also mean that the urbosphere itself has become a source of pollution. Contaminated urban soils can be sources of contaminants for surface water and groundwater (Wong et al. 2012). Transfer of material from soil to air by wind is a recognised factor in decreasing urban air quality (Almeida et al. 2005; Sillanpää et al. 2006), and soil to atmosphere fluxes may also introduce contaminants to other ecosystem compartments (Laidlaw and Filippelli 2008; Reis et al. 2013). Possibly the most critical effect on atmospheric air composition is from the emission of greenhouse gases; urban areas are the single major contributor of global anthropogenic greenhouse gas emissions, with soils adding to overall urban emissions (Bellucci et al. 2012). The ability of urban soils to act as both a sink and source for pollutants will be covered in Chap. 9, along with frameworks for estimating risks from polluted urban soils.

The health of soils relates positively to human health, in terms of both physical and psychological well-being (Swartjes 2015; Brevik and Pereg 2017). In urban environments, people's quality of life is improved by soil-related activities such as gardening, which provide benefits including improved mental health and community connectedness (Wakefield et al. 2007; Soga et al. 2017; Laidlaw et al. 2018). Conversely, degraded soils, especially if contaminated, pose multiple ongoing threats to human health (Filippelli et al. 2012; Pepper 2013). The health effects of soils are unevenly distributed in cities, and this is one focus of the *environmental justice* movement. For example, lower socioeconomic groups in a city are known to be exposed to, or affected, more severely by soil pollution and can also have less access to beneficial soil-related activities such as use of public open space (Zhuo et al. 2012; McClintock 2015). This book will explore the relationships between soils and human health in urban systems, in the context of the United Nations' Sustainable Development Goals, in Chap. 10.

There is, however, still cause for optimism about the health of urban soils. Along with the multitude of forms that soil degradation can take in cities, there are an increasing number of options for *soil remediation* (Bolan et al. 2014), from simple revegetation to highly technical methods such as electrokinetic migration (Ho et al. 1995). Many soil remediation techniques have been developed for urban environments, but others were developed for environments such as waste facilities and mine sites. As a result, some urban soils are becoming, or being made, cleaner as pollution sources are removed or better controlled and as land is rehabilitated (Andersson et al. 2010). The prevalence of degraded soils in urban environments makes cities ideal environments to study the options for land rehabilitation, and this topic is covered in Chap. 11.

Although urban environments and soils are very distinctive, it will become apparent that we can use many of the concepts in traditional soil science to understand and analyse urban soils (Fig. 1.6). It will also become clear, however, that urban soils show multiple differences from their non-urban counterparts and this, together with existing in distinctive and increasingly crucial urban ecosystems, makes urban soils an essential subject to study within the wider discipline of soil science.

1.6 Additional Reading

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1.7 Summary

- Globally, soils are a keystone of the critical zone, the upper layers of Earth's land surface which sustain terrestrial life.

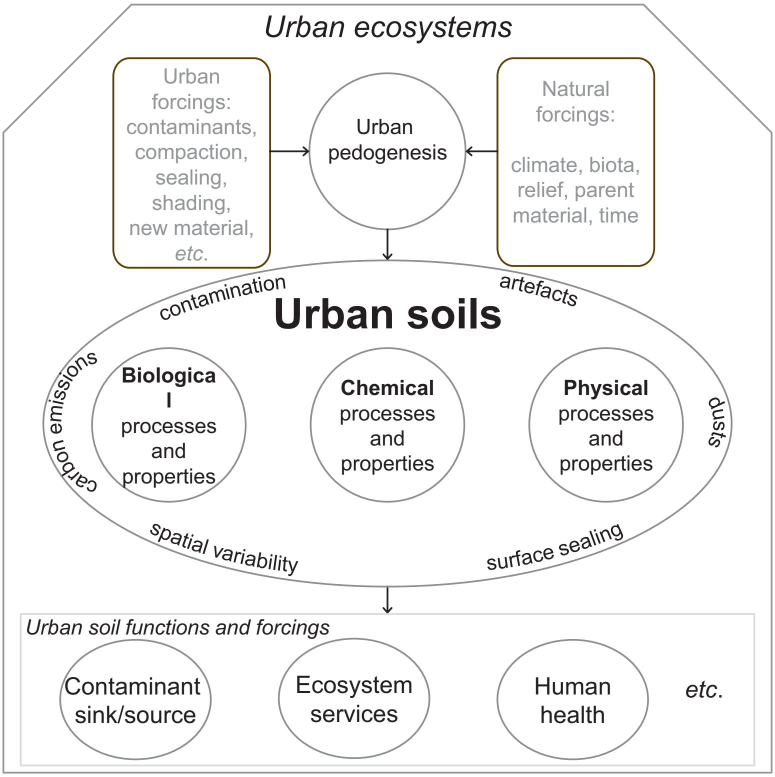

Fig. 1.6 Conceptual diagram for urban soils within urban ecosystems, showing selected examples of their key drivers (forcings), properties, and ecosystem functions (graphic by Andrew W. Rate)

- The beneficial properties of soils have in many cases been a factor determining the location of cities; conversely, urbanisation has affected, and often degraded, the properties of soils.
- Human populations in urban areas are increasing rapidly, and urban soils will increasingly be needed to support these populations, while simultaneously being affected by human activities.
- Urban soils may show multiple differences from natural soils but may also perform many of the same ecosystem functions. Conventional soil science concepts, therefore, still have a part to play in understanding urban soil environments.

1.8 Questions

1.8.1 Checking your Understanding

1. What is the critical zone, and how does is relate to urban soils?
2. Give some examples of how humans use soil in cities or are affected in some way by urban soils.
3. Historically, how did the fertility of soils affect the development and location of cities?
4. What are some of the distinctive characteristics of urban soils?
5. List some of the ways in which urban soils have their chemical and physical composition changed.
6. What biological changes might you expect in urban soils as modification and disturbance caused by humans increases?

1.8.2 Thinking about the Issues

7. If increasing areas of urban and peri-urban land will need to be used for food production, what are some of the soil-related issues that might limit this kind of use?
8. Is the proposed existence of the Anthropocene a useful concept for understanding urban soils? Discuss your reasoning.
9. Is it possible that urbanisation could improve the properties of some soils? How?

1.8.3 Contemplating Urban Soils Creatively

10. Would you expect the environmental effects of urbanisation to differ for cities which have expanded in geographical extent at different times (e.g. expansion in the first versus the second half of the twentieth century)? Explain your reasoning and what the difference might be.

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