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Altered resources, disturbance, and heterogeneity: A framework for comparing urban and non-urban soils

S. T. A. Pickett · M. L. Cadenasso

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Abstract We propose a framework of key concepts useful in understanding how urban soils can contribute to general ecological theory. The major factors that can cause urban soils to be different from soils in non-urban ecosystems are identified and related to the familiar state factor approach. We evaluate directly altered resource availability, and the role of stress in mediating resource availability in urban ecosystems. Modified groundwater and stream flow, and atmospheric deposition of nitrogen and base cations are particularly important resource fluxes to soils in urban ecosystems. Disturbance can be conceptualized in the same way in urban as in non-urban ecosystems. However, in addition to biophysical disturbances familiar to ecologists studying wild lands, demographically and socially mediated changes in ecosystem structure must also be considered. These changes include human migration and population structure, institutional shifts, and the effects of human health. Finally, spatial heterogeneity, including fragmentation and differential connectivity, integrates the effects of resources and disturbance, and has an effect on subsequent resource availability and susceptibility to disturbance. Layers of heterogeneity include not only the geomorphic template, but urban climate, biotic composition, buildings and infrastructure, and demographic-social patterns. The complex layering of natural and social factors that constitute urban heterogeneity permit the continuation of important ecological processes, as well as modify ecological fluxes involving soils. We present a modification of the state factor approach as an expanded framework for the study of urban soils. The understanding of urban soils can contribute to general ecological theory by testing the generality of important ecosystem drivers and their linkage with social processes in an under investigated ecosystem type that is increasing in extent and impact worldwide.

Keywords Disturbance · Framework · Human · Soil · State factors · Urban · Heterogeneity

S. T. A. Pickett (✉)
Institute of Ecosystem Studies, Box AB, Millbrook, NY, 12545, USA
e-mail: PickettS@ecostudies.org

M. L. Cadenasso
Department of Plant Sciences, University of California, Davis, 1 Shields Ave., Davis, CA 95616, USA

Introduction

This paper helps lay a conceptual foundation for a series of papers exploring how understanding urban soils can contribute to ecological theory. The contribution of an area of science is often judged by its valid generalizations, broadly applicable models, or its concepts of wide interest. In particular, the organizers of the series (Pavao-Zuckerman and Byrne 2008) posed two focal points for the collection. First they asked, what characteristics of urban systems make the soils in them similar or different from those in non-urban ecosystems? Second they asked, can a focus on resource availability, disturbance, and heterogeneity promote integration within urban soil studies, and link that topic with broader research areas? These two questions are specific cases of ones that would be asked of any area of research to evaluate its general significance and coherence: How is the system of concern similar to or different from other systems, and what conceptual framework promotes comparison within a discipline and with other disciplines? We will articulate a conceptual framework to help focus future research into the soils of urban ecosystems.

A specific goal of this paper is to define the key types of resources, disturbances, and kinds of heterogeneity that might affect urban soil genesis and functioning. Unfortunately, there is no single technical definition of "urban" that applies to all policy or research situations (McIntyre et al. 2000; Theobald 2004). However, it is important to emphasize that by urban, we mean the broad array of habitat types that might be encountered in a metropolitan area, ranging from the central city, through suburbs, to exurbs, and finally to the connected hinterlands of the city. Urban in the broad sense therefore refers to densely settled landscapes having permanent infrastructural installations, and that support industrial or service economies, spatially extensive commuting or information networks, and residences for workers in those sectors. Urban areas are heterogeneous mosaics that include both "green" and "grey" land covers. These mosaics interdigitate with or contain wildlands. In addition, we recognize that contemporary metropolitan areas are complex, multi-centered urban aggregations, rather than simple bull's-eye patterns of declining built and human density and land use (Gottdiener and Hutchison 2000). The multinucleate nature of contemporary conurbations is unlikely to exhibit literal gradients from a center to a periphery. Rather, the contemporary "city" has many cores and edges (Garreau 1991). This complexity makes for many kinds of interactions with soil. Each specific empirical or modeling study of an urban system is obliged to define the scope of "urban" it employs (McIntyre et al. 2000).

A foundation from soil science

One of the most familiar frameworks in the environmental sciences is the state factor approach to soil formation (Jenny 1941). We therefore take this as a starting point for exploring the generality of research on urban soils. This approach identifies (1) climate, (2) landform, (3) organisms, (4) parent material, and (5) time as the complete set of causes of soil formation. The state factor framework has suggested that coarse scale gradients of one or more of these factors be used to organize and explain the variety of soils over large regions. Interactions of the different factors is of course, a possibility.

The five state factors are powerful precisely because they embody the principal causes of soil formation, and each general factor incorporates more specific mechanisms (Coleman and Crossley 1996). Frameworks, such as the state factor approach, typically identify the general causes of a phenomenon, within which are grouped more specific mechanisms (e.g., Pickett et al. 1987; Pickett and Kolasa 1989; Cadenasso et al. 2003). Climate includes the major drivers of temperature and water availability. Seasonality and duration of different temperature and moisture conditions are key modifiers of the basic climate factors. Temperature, of course, is a master climatic variable controlling the rates of chemical and biological processes of weathering, chemical reactions, and metabolism of the organisms that live in and on the soil. The water regime, both in its timing and amount, controls the rate and direction of transport within the soil body, including leaching, evaporation, lateral transport, upward capillary action, and transpiration. Landform is a relatively local modifier of the factors of climate, including especially the more local run-on or runoff of water, deposition of parent material, solar radiation budget, and vegetation. Examples of climate and landform interaction include north versus south facing slope effects, or local modification of water available for transport of soil constituents resulting from small swales. Organisms are local and regional engines of metabolism. They also act as agents of transport against or with gravity, and amplify or dampen seasonal patterns through their phenology. Parent material can vary from regional to local scales. It determines the basic raw materials for weathering, the availability of most mineral resources, and plays a major role in the capacity of the soil to hold or shed water, thus interacting with the features of climate. The spatial pattern of parent materials may vary on extremely local levels, sometimes determined by land form and sometimes by organisms. Effland and Pouyat (1997) have emphasized the importance of new or highly modified parent materials in urban systems, indicating that anthropogenic soils are developed in such substrates. Time, beyond seasonal fluctuations, is the final state factor. It is important for the processes of weathering, organic matter accumulation, decomposition, and plant community colonization, establishment, and change. These processes influence the physical and chemical attributes of soil.

How do these five drivers of soil formation translate to the urban realm? To make that translation we must identify how physical conditions and biotic agents in urban areas, as well as specifically human derived patterns and processes, affect the soil state factors. This will lead us to construct a hierarchical, causal framework based on the state factors, which includes urban systems. Frameworks indicate what the possible causes of structure and dynamics in a subject are, and organize those factors. The potential causes are the raw material for dynamic, predictive, or mechanistic models. The framework we present can accommodate the kinds of modifiers each factor may experience in urban systems compared to the more familiar agricultural and wild land soils (Fig. 1). Following the hypothesis posed by Pavao-Zuckerman and Byrne (2008), we seek the modification of the state factors in three characteristics of urban systems compared to non-urban ecosystems (Pickett et al. 2001; Breuste et al. 1998; Craul 1992): (1) altered resource availability, which may be taken to incorporate both the absolute size of resource pools, as well as stress factors that modify resource availability, uptake, or use by organisms; (2) disturbance, events which can alter soil structure directly, or which modify other social and ecological structures that influence urban soils; and (3) the spatial heterogeneity in the state factors and the modifying factors of resource availability and disturbance.

In other words, our task is to enumerate the urban manifestations of the state factors. We will summarize urban conditions that have the capacity to modify the state factors in urban systems. We group these specific modifying factors under the broad processes of altered resource availability, disturbance, and spatial heterogeneity. The enumeration of specific factors is not exhaustive, but rather illustrates the kinds of effects that may cause urban soils to differ from non-urban soils.

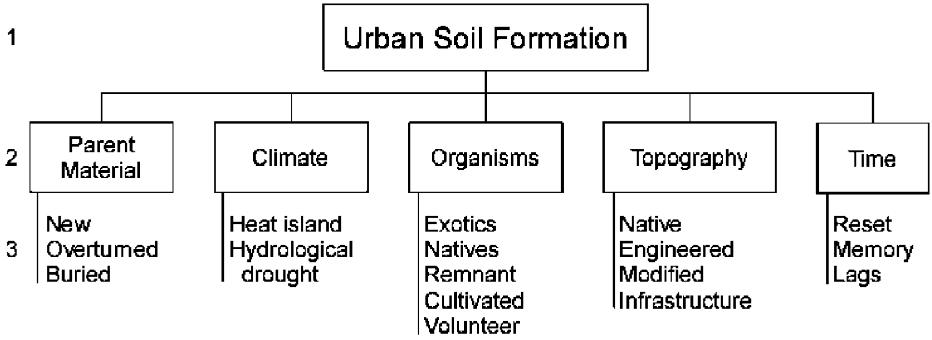

Fig. 1 The five state factors of soil formation originally proposed by Jenny (1941), along with a listing of general conditions and processes that are particularly relevant for soil formation in urban ecosystems. The *top level* of the causal hierarchy identifies the process of interest. The *second level* indicates the contributing causes of that process, in the form of the five state factors recognized by Jenny (1941). The *third level* of the causal hierarchy indicates some of the prominent features of urban environments that can influence soil, in contrast to the situation in most non-urban soils. In particular, urban parent materials may include new materials, and overturned or buried horizons. Urban climate is modified through such processes as the urban heat island and hydrological drought based on storm drainage infrastructure and impervious surfaces. Organisms in urban ecosystems include newly introduced exotics, as well as remnant native vegetation, cultivated and non-managed volunteer vegetation. Altered microbial communities must be considered as well. Topography includes the native lay of the land, as well as new engineered or modified surfaces and slopes. Because topographically driven processes will often be modified by infrastructure such as roads and storm drains, we include that major urban feature here. Finally, time includes the resetting conditions with land cover change, changes in input or flow of pollutants and stress factors, and the duration of time over which those factors apply. Lagged effects, echoes of past conditions, and memory of prior states of the system are complications that appear in urban areas. The connections from higher to lower levels means "is composed of." Details are developed in the text

Urban modification of resource availability

Altered urban resource availability involves water, nitrogen, base cations, and heavy metals. Water in urban soils is modified by the limited infiltration, and by increased runoff in storm drainage infrastructure. Infiltration is limited by the sealing of urban soils, and by the compaction of soil surfaces that remain unsealed. Runoff is increased by the existence of pavement, roofing, and other surfaces that drain into storm sewers. Consequently, urban soils are typically drier than non-urban soils in mesic areas (Hough 1995). However, in arid zones, illustrated by Phoenix, AZ, where irrigation water is readily available, this trend is reversed (Brazel et al. 2000). In addition to the general decrease in soil moisture content, there is a lowering of water tables in mesic urban areas (Sukopp et al. 1990; Hough 1995). Lowered water tables no longer interact with flood plain soils, and, typically, organic matter, anaerobic conditions and denitrification decrease (Groffman and Crawford 2003; Groffman et al. 2003). In addition, because storm drainage is often channeled directly to urban streams through pipes, the flow rates and flood depths are often extreme. Such large discharges give urban streams their "flashy" characteristic and erode urban streams deeply into the substrate, sometimes to bedrock. Eroded, incised urban streams further reduce the supply of soil water to riparian zones. The net result of all these phenomena is urban "hydrological drought" (Groffman et al. 2003). Despite high levels of rainfall in many temperate metropolises, the water budget is so altered that much less water is readily available to plants and for the base flow of streams (Paul and Meyer 2001). Such alterations are general enough that they are identified as an "urban stream syndrome" worldwide (Walsh et al. 2005).

Nitrogen is a key limiting resource in terrestrial systems, and, in the form of nitrate, is a ground water pollutant. Nitrogen levels are enhanced in urban systems because of lawn fertilization and landscape plantings (Law et al. 2004), the conversion of human and animal food into sewage (Grimm et al. 2003), and the exhaust from automobiles (Vitousek et al. 1997). Automobile exhaust generates deposition of particles or of dissolved oxides of nitrogen from the urban atmosphere. Some metropolitan areas have demonstrated higher nitrogen loadings to the soils in zones where traffic is most concentrated (Medley et al. 1995). The additional nitrogen boosts soil metabolism and affects litter dynamics (Pouyat et al. 1995). The urban environment even increases nitrogen metabolism in rural soils transplanted to city sites (Pouyat and Turechek 2001). Deposition of N may extend well beyond cities and suburbs themselves, to impact N dynamics of nearby forest and lake systems, as they do in the urbanizing Colorado Front Range (Baron et al. 2004).

Ecosystems typically retain nutrient elements that are biologically active or limiting. A theory of nitrogen dynamics in forest ecosystems posits that once the capacity of a system to sequester or retain a limiting nutrient is satisfied, or saturated, that element begins to leak from the ecosystem (Aber et al. 1998). Urban ecosystems may sometimes retain a surprisingly high amount of nitrogen. Presumably, this is at least partly a result of the remnant or unbuilt patches that exist within the larger urban ecosystem, or well watered ornamental landscapes (Groffman et al. 2003).

There are two other major chemical features of urban soils that are important: base cations and heavy metals. Base cations are often especially abundant in urban soils because of the erosion of building materials, such as concrete and limestone building blocks (Jim 1998; Pouyat et al. 2007). As these calcareous materials erode, calcium and related base cations are deposited in the urban environment. Because of the interaction of base cations, pH, and availability of macro- and micro-nutrients, the calcium enrichment of urban soils is a significant urban factor (Pouyat et al. 2007). There may be altered stoichiometry in urban systems as a result of such enrichment (Kaye et al. 2006).

Urban soils are also typically enriched in heavy metals, such as lead, chromium, copper, and zinc. The over availability of these metals leads to toxicity in plants, microbes, wildlife, and humans. Heavy metals have entered urban soils primarily through industrial manufacturing, lead based paints, lead based antiknock compounds in automobile fuel, and the wear and tear on tires, brake linings, building materials and fencing, treated timber, etc. (Pouyat and McDonnell 1991; Callender and Rice 1999) These materials pose serious health problems for humans, and can affect ecosystem processes (De Kimpe and Morel 2000; Mielke and Reagan 1998).

Disturbance in the urban context

Disturbance refers to an event that alters the structure of an explicitly specified system. Subsequent to the event, resource levels in the system can be altered directly as a result of the loss of a key structural component that acts as a source or a sink of a resource, or filters the flows of a resource. Disturbance can affect resources indirectly as the result of stresses on physiological or ecological processes that a structural alteration creates. Neither the existence nor the effect of disturbance can be assessed without the explicit specification of a model of the system of interest. Such a model would specify the three dimensional structure of the system, the components that contribute to that structure, the process linkages among components, the system boundary, and the temporal limits of the system. All this is required for rigorous use of the scientific concept of disturbance (Pickett et al. 1989; Pickett and White 1985).

In urban systems it is necessary to understand disturbances that originate with biogeophysical events, disturbances that originate with human actions, and those that are a hybrid of the two. In addition, though the physical alterations caused by the disturbances are short, the response to them can be either persistent or transient (Table 1). Consequently, the realm of possible interactions and effects is huge. Given that bioecological attention to urban systems is relatively new, such rigor is important to sort through the many new kinds of data on urban systems that are accumulating.

This rigor is especially relevant in discussing soils. Because soils are profoundly affected by their physical composition and structure, and because these soil components have long "memory" (Johnston 1991), understanding the persistent effects of transient events or of

Table 1 A scheme illustrating the complexity of ecological events, and showing the relationship of disturbance to the larger universe of ecological events

Event		Effect	Release
Onset	Duration		
Sudden	*Short*	*Short*	None
			Gradual
			Sudden
		Persistent	None
			Sudden
			Persistent
	Persistent	Short	None
			Sudden
			Persistent
		Persistent	None
			Sudden
			Persistent
Gradual	Short	Short	None
			Sudden
			Persistent
		Persistent	None
			Sudden
			Persistent
	Persistent	Short	None
			Sudden
			Persistent
		Persistent	None
			Sudden
			Persistent

Disturbance is defined as a sudden event that disrupts the structure of an ecological system as represented by an explicit model, is indicated by italicized entries in the appropriate cells. A specific disturbance, initiates one pathway out of the possible pathways through the table. Ecological events can all be characterized by the suddenness of onset, the degree to which their effects persist, and whether and how quickly the effects are released. Structural disruption in urban areas often has persistent duration due to human design. Not all possible pathways from event, through effect, to release, have explicit or distinctive labels in ecology. Even the terminology of "press and pulse" does not encompass the refinements to events expressed in the body of the table. Soils can be affected by events having a variety of trajectories from onset, effect, to release. The specific actions involved in each step, represented by columns in the table, would have to be discovered in order to fully understand the mechanisms of soil formation, disruption, and functioning in any ecological system. However, the complexity of causation in urban areas, involving both biophysical and socio-economic causes requires special care in elaboration long forgotten press events, is crucial. Discrete events of dumping, filling, spilling, digging, and planting, for example, can have lasting effects on urban soils and the waters and organisms that contribute to their structure and function (Effland and Pouyat 1997). Similarly, the periodic alteration of human activities, through bouts of innovation and sudden shifts in fashion in human societies can result in shifts in the spatial and temporal distribution of different kinds of disturbance, referred to as a disturbance regime (Pickett and White 1985).

Biogeophysical disturbances In order to apply the disturbance concept to the urban context, we start with events that have a large biogeophysical component. We ignore for the moment the effects that human generated global change can have on the coarse scale drivers of these events. Biogeophysical disturbances can be caused by floods, wind, earth movements, and organisms.

The location of so many human settlements on the banks of streams means that floods can readily disturb urban areas. Huge floods are remarkably common, and may significantly change urban structure or management (Barry 1997; Colten 2005). The 1927 and 1993 floods of the Mississippi River, and the 1937 flood of the Ohio are cases in point (Platt 1999). The flooding resulting from storm surges raised by hurricanes or typhoons is illustrated by Hurricanes Katrina and Rita in 2005 and was likewise predictable in a general sense (Fischetti 2001). Although the magnitude, onset and duration of riverine flooding is unpredictable in detail, the recurrence of severe river floods is one of the most common of natural cycles. The largest floods typically recur at lower frequencies (Dale et al. 1999), but climate change, alteration of land cover of the upstream catchment, and the accumulated changes in channel form and management are associated with increased frequencies of intense floods. Even the tsunamis which affected South Asia in December 2004 after a submarine earthquake were not without precedent. The 1883 eruption of Karakatoa produced similar devastating coastal disturbance (Winchester 2003). These sorts of events, and the infrastructure installed to deal with them, affect urban soils through altering sediment loads, ground water levels, soil aeration, and subsidence (e.g. Colten 2005).

Wind storms take the form of downdrafts, tornadoes, hurricanes and typhoons. In the case of the large cyclonic storms, rainfall is often as much the agent of disturbance as the high winds. The lower intensities of windstorms damage and uproot trees and bring down utility wires in urban areas, while the more severe storms can damage or destroy even well fitted buildings. The 1989 Class 4 ("Severe" on the Fujita Scale) tornado in the Allegheny Plateau of Pennsylvania blew down 400 ha of old growth forest, uprooting huge root plates and leaving adjacent deep pits, while it converted boles, branches, leaves and needles to litter (Peterson and Pickett 1995). The same alteration of soil structure and conversion of biomass to litter occurred in cities and towns of the region.

Fires are an urban phenomenon as much as a wildland one (Pyne 2001). The constraints of fuel, ignition, and control are basically the same for urban and wild land fires, although the detailed causes of these factors differ. Great urban fires were common in colonial and industrial cities up through the beginning of the twentieth century (Smith 1995). The last two great urban fires in the United States were those in Baltimore in 1904 (Olson 1997), and the 1906 fire in San Francisco (Winchester 2005), which was associated with the earthquake and subsequent management actions. Highly impactful urban fires still threaten under served informal settlements in the rapidly growing megacities in the global south. Great urban fires have resulted in large amounts of rubble that have typically become parent materials used to alter shorelines and urban riparian and wetland zones (Olson 1997).

Earth movements are sources of disturbance in settled areas (Anonymous 2006). These include earthquakes, and catastrophic landslides and mass wasting from slopes during earthquakes, saturating rains, or construction (Garwood et al. 1979). Although earthquakes are associated in the minds of many with subduction zones where tectonic plates intersect, there are other sites where huge earthquakes occur as well. For example, there is evidence of large pre- or early-settlement earthquakes in such seemingly taciturn geologies as the eastern United States. Charleston, South Carolina occupies a coastal site having prehistoric evidence of large quake activity. Further inland, near the confluence of the Mississippi and Ohio Rivers, the New Madrid Fault unleashed a tectonic event that may have been the equivalent of eight on the Richter Scale (Johnston and Schweig 1996). It is only through the occurrence of this event in 1811, before there were large cities built of brick in the lower Midwest, that notoriety has been avoided. Of course, the estimate of Richter 8 is based on effects in cities quite a distance from the epicenter. Instrumental measurements of this event are unavailable. Future activity along this fault would affect Saint Louis, Memphis, and Louisville, among others, quite severely. Earthquakes can not only generate debris which has the potential for becoming new parent material, but the opening of previously sealed soils is likely. The Alaska earthquake of 1964 illustrates the effect on soils, as coastal areas were submerged, or blocks of terrain were raised or lowered relative to one another. New soil formation, burial of existing horizons, and alteration of drainage patterns and soil water would be important local urban effects.

Biotic disturbances Biotic disturbances in the urban fabric cannot be neglected. Defoliation of urban trees by periodical insect emergence, and the depredations by introduced pests and plant diseases have altered the structure of many cities (MacFarlane and Meyer 2005; Nowak and McBride 1992). The introduced Dutch elm disease reduced the canopy cover of many eastern American cities, and some have yet to recover their former greenness. Rats and fleas as disturbance agents affecting the human population directly is another biotic disturbance (Yates et al. 2002). Events of a biotic origin include the acclimation of foxes to urban habitats and their spread in America and Europe. Deer in some areas are becoming a persistent agent of change in the urban landscape. Soils can be affected by biotic disturbances that alter carbon input instantaneously, alter its allocation in the ecosystem, and cause sudden pulses of nitrogen via defoliation. Change in food webs can alter the soil components as well, if dominance shifts between consumers and decomposers, for example.

In looking back over the examples of “natural” disturbances presented above, it is clear that such events can affect urban soils quite dramatically. A framework focuses on the possible mechanisms of control and alteration. To summarize potential disturbance effects, the distribution of sediment after floods, or the disposal of post flood sediment can affect urban soils. Similarly, fires can generate debris that becomes a new parent material as well. Carbon sequestration in urban systems, particularly through the soil component, can potentially be altered by fire. Wind storms generate much organic matter, some of it leaf litter that is richer in nitrogen and other nutrients than it would have been had the leaves senesced naturally. Earth movements cause the shift of land uses or covers, contribute to pulses in the real estate cycle or alter social structure. For example, the destruction of the Cypress Freeway in Oakland, California during the 1989 Loma Prieta earthquake and the subsequent restoration of the surface boulevard changed land cover. Organisms as disturbance agents alter the canopy structure of cities, with its attendant micrometeorological alteration, effects on property values, and on perceptions and use of land by people.

Social reorientation, differential migration by class or race, and institutional reorganization are all potential human responses to disturbance that affect how soils are perceived and managed.

Demographic and social disturbances Ending the previous section with a nod to mixed biophysical and social responses to disturbance and alteration of resources and environmental controls, brings our full attention to disturbances that are the result of social processes. The richness of possible causes of such disturbances is illustrated by the human ecosystem framework, an enumeration of the potential linkages of the many human structures, perceptions, and actions that must affect all settled and managed ecosystems (Force and Machlis 1997; Machlis et al. 1997; Fig. 2). In other words, people, their social and cultural tools, and the structures they build are possible mechanisms for disturbance in the system. Here it is important to note that disturbances can have either positive or negative effects, depending on the perspective from which they are viewed. For example, disturbance to a forest canopy is a "negative" impact on the mature trees that are uprooted and killed, but a "positive" impact on the seeds and seedlings of other species that had been suppressed in the understory. Similarly, disturbances of a social, economic, cultural, and demographic nature may be perceived as good or bad by different people, and have differential impact based on location, social status, the availability of different kinds of capital, and so on. Indeed, innovations, as recognized as early as the work of the Chicago School in the 1920s (Gottdiener and Hutchison 2000), may be considered disturbance in the sense we have established in this paper—an event that alters the structure of a system and may have subsequent impact on resource availability, signals, and stress factors. In applying the disturbance concept to urban systems, it will therefore be crucial to avoid an informal and strictly negative use of the term.

Often ecologists speak inappropriately of urban areas as being disturbed relative to non-urban ecosystems, or they speak of humans as uniformly being a disturbance

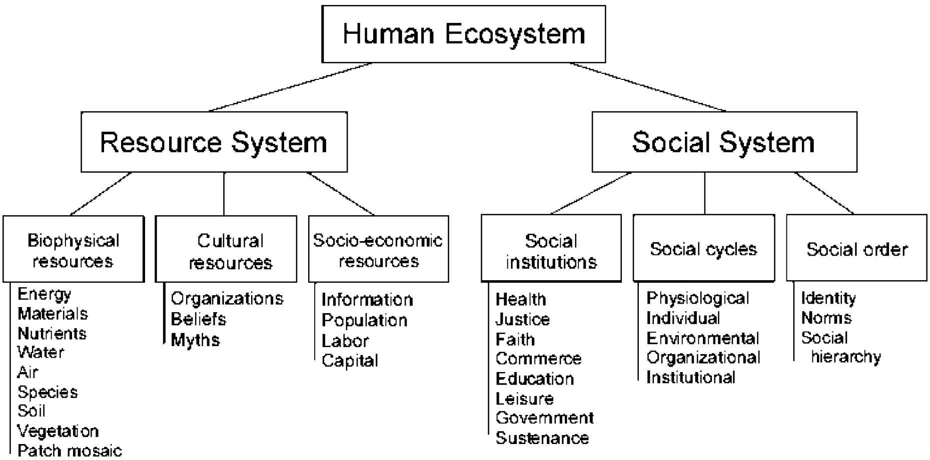

Fig. 2 A general diagram of the major components of the human ecosystem framework. Human ecosystems comprise a resource subsystem, and a human social system. The resource system includes biophysical resources, cultural resources, and socio-economic resources. The social system includes social institutions, social order, and temporal changes in these processes under the rubric of social cycles. The more specific components of each compartment are enumerated. Modified, with additions, from Machlis et al. (1997)

(Bart and Hartman 2000). Certainly, some human actions alter the structure and resource availability in defined systems. Equally clearly, urban and non-urban ecosystems differ in the potential targets and agents of disturbance. It is also important to recognize that not all disturbances in urban systems connote the negative implications of the vernacular use of disturbance.

We can only illustrate the richness of social and demographic disturbances here. The human ecosystem framework (Fig. 2) suggests that urban disturbances may originate from a wide variety of human sources. The components of the human ecosystem framework are system elements that would be selected among to construct models of system structure. Thus, the human ecosystem framework is the basic tool for identifying how urban soils can be impacted by anthropogenic disturbance. We use examples from (1) migration, (2) institutional changes, (3) health and morbidity, and (4) investment and disinvestment. Such processes can affect urban soils through location and establishment of new infrastructure and buildings, abandonment and demolition of buildings, input of resources and pollutants in urban soils, and alteration of stress factors on soils and affects on human management decisions.

Migration of people may disrupt the structure of part or all of an urban system (Gutman et al. 2005; Redman 2005). Migration may produce a deficit or surplus in age structure or sex ratio in specific neighborhoods or settlements. Furthermore, migration may alter political and social networks, and change the demand or availability of human and social capital. Where in the city specific ethnic populations or social groups chose to or were allowed to settle influences infrastructure and the density and status of building stocks. Of course, migration per se does not directly affect urban soils; however, the changes that follow from massive accommodations and redistributions of human populations do indirectly affect urban soils. If migration results in new construction, installation of new infrastructure, increased industrial and transportation based pollution, changes in the type and cover of urban vegetation, and so on, these subsequent changes can impact urban soils. Although infrastructure may seem to be a permanent fixture resulting from migration, how infrastructure is used may change, and soils change as a result. Uses such as lawn watering, street sweeping or rinsing, landscape planting, and grounds maintenance on different properties are all examples of social processes that affect soil function and sometimes structure.

Institutional changes are another agent that may disturb features of urban systems. "Institution," refers to the ways that people organize themselves for social purposes. Institutions can include both transient and persistent associations, formal and informal structures, profit-making corporations and organizations aimed at the public good, productive and service organizations, and governmental and non-governmental structures (Machlis et al. 1997; Costanza et al. 2001). Households, clubs, religious congregations, schools, agencies, community groups, businesses, and gangs are but a few examples of the range of institutions that exist in human ecosystems. Because institutions manage natural resources, decide on the condition and state of lands, build, renovate, and raze architecture, and shape where and how people use land, the nature and condition of institutions has much to do with the condition of urban soils (Grove et al. 2006). The increase in soil organic carbon in both semi-arid systems such as Colorado (Kaye et al. 2005), and mesic systems such as Baltimore, is substantial, and reflects urban convergence driven by similar institutional motivations and behaviors (Pouyat et al. 2007). Changes in the institutions are important. For example, change in the institution of agriculture affect whether farmers on the urban fringe maintain their soils in an undeveloped state, or whether those lands are developed into residential, transportation, industrial, or other urban purposes, often with large implications for the soils in those areas.

Institutional changes in the inner city may influence whether older housing is renovated or torn down, with consequences for the unsealing and further pedological development of soils in the city. The activities of a community group may separate a neighborhood with high residential abandonment from one with intact housing. For example, the Parks & People Foundation in Baltimore facilitates the reclamation of abandoned land by removing paved surfaces, planting vegetation, and establishing community gardens. These restoration efforts alter urban soils (Pickett et al. 2007).

Changes in human health and morbidity are further examples of potential urban disturbances. For example, the cholera epidemics in Baltimore in the 1880s helped spur suburban development, with associated changes in soil coverage and vegetation (Boone 2003). Similarly, the construction of Baltimore's sanitary sewer system in 1911 was motivated in part by these events. The organic content and microbial ecology of Baltimore's urban soils undoubtedly changed markedly as a result. Health effects of extreme weather illustrates that a single event can also be significant. Such events can act as a disturbance to the social system in one area, but not another. Hence it is not the weather per se that is a disturbance, rather it is the interaction between weather and a social system—in this case represented by the social capital of different neighborhoods—that is the disturbance. The Chicago heat wave of 1995 is a textbook example of this interaction (Klinenberg 2002). Mortality, the index of disturbance, was greater in poor neighborhoods lacking social networks to care for the heat sensitive elderly, compared to neighborhoods that were culturally better networked. Fear of crime, a specific indicator of low social capital, was a contributor to keeping sensitive older people inside of stifling residences in some neighborhoods that were hard hit by the heat wave. While this event has not so far as we know been investigated in terms of any soil effects, changes in neighborhood structure may well affect soils. If disturbance related mortality removes sources of wisdom about gardening, depletes the ranks of advocates for neighborhood greening, or attenuates the number of activists engaged in preventing dumping on vacant lots, there is the potential for subsequent alterations of the structure and function of soils in the area. These are hypotheses to be tested about the role of social disturbance on urban soils.

The investment or disinvestment in buildings and infrastructure provides a final example of social disturbance in metropolitan regions (Greenbaum 1993). The investment in a new highway route, for example, is an event that changes the structure of parts of the metropolitan system. Following on this event, which of course puts in place a relatively persistent new structural element, new commercial, residential, and industrial developments are made, which alter vast areas of soil. Likewise, disinvestment in many central city neighborhoods, often related to the opening of suburban lands and highways providing access, may be considered an event that triggers abandonment and demolition, with effects on soils (Hayden 2003). Soils that had been sealed may be exposed to the open air for the first time in decades or even centuries in such neighborhoods. In addition, macronutrients from building materials are added to the particulate matter that enters soils (Pouyat et al. 2007). Drainage patterns and infiltration to ground water may be altered by investment versus disinvestment in buildings and infrastructure. The spread of exotic plants and soil organisms can follow new infrastructure.

Spatial heterogeneity

Although some areas of a metropolis are homogeneous for certain scales and attributes, the spatial heterogeneity of cities is legendary. Homogeneity characterizes tract developments, row house neighborhoods, ethnic enclaves, and singe use zoning (Shane 2005). However, in spite of such patches of homogeneity, much of a city and its other associated settlement space is remarkably patchy at fine to medium spatial scales. Urbanists comment on the rapidity with which one neighborhood transitions into another (Clay 1973). Similar changes are common: a bustling commercial district might abut a dead industrial zone; a high speed transportation corridor borders a sleepy residential enclave. Understanding the different degrees of heterogeneity at different spatial scales is important for describing and functionally evaluating urban heterogeneity (Cadenasso et al. 2006). Soil structure and function may follow the spatial heterogeneity in cities. Some patches serve as sources while others are sinks for resources, such as C or N (Riemann 2003). The juxtaposition of patches or their connectivity by overland flow or by networks of infrastructure are key aspects of heterogeneity.

There are many sources of spatial heterogeneity within urban areas. We cannot review them all here, but we will focus on five large classes of heterogeneity that are important in cities. Climate is the first. While climate may appear to be such a broad scale phenomenon that it would not vary within the metropolitan matrix, it does in fact have a heterogeneous distribution at the scale of urban regions (Oke 1995). Rainfall differs from place to place, even during a single storm event. Hence convectional storms produce areas of intense flooding while other areas nearby remain dry or sparsely wet by the same event (Smith et al. 2005). Other aspects of climate also vary. Wind is affected by the height and distribution of buildings, with skyscraper “canyons” being particularly windy. The presence or absence of trees or of extensive lawns affects wind and humidity. Trees also mediate the amount of particulate matter in local areas, and tree canopies affect local solar radiation loads. Particulate matter aloft increases the probability of rainfall downwind. Regional “domes” of carbon dioxide concentration and of temperature are centered on dense urban nuclei. In the case of temperature, the enhancement has been labeled the “heat island” when compared to the temperatures outside of cities (Oke 1995). The heterogeneity of urban climate is, as a consequence of these overlapping layers of pattern, quite complex. Because moisture and temperature are important in regulating biological processes in soils, heterogeneity in these features can affect the activity in specific parcels of soil (cf Kaye et al. 2005). Similarly, localized concentrations of nutrients or heavy metals can affect soil processes (Pouyat and McDonnell 1991).

Another source of heterogeneity in the metropolis is topography and land cover (Spirn 1984). In the case of topography, the basic land form usually remains as a broad template for urban development. The existence of escarpments with their waterfalls or rapids is a signature of many Eastern US cities. Harbors and bays, although subject to massive filling projects, remain features of coastal cities. Steep sided stream valleys in cities are often the location of sparse development, or of large urban parks. The rolling hills or ridges of some cities give them their basic form, in spite of massive movements of earth associated with construction of buildings, roadbeds, and parking facilities. Indeed, geologists estimate that humans now move more earth worldwide than do natural geologic processes (Wilkinson 2005). This implies that the location of parent materials and the ages of many soils in settlements is a human artifact. Rock outcrops and cliffs persist in some cities, and are the habitat of remnant, sometimes rare, vegetation and animals (Larson et al. 1999). The topography of cities, towns, suburbs and villages is thus a combination of native and constructed or modified surfaces. The native soils have been ignored in many cities, and soil classifications of many urban areas neglect natural processes (Effland and Pouyat 1997).

Infrastructure adds its own layer of heterogeneity. The piping of drinking water, and the network of sanitary sewers and storm drains connects new watersheds in urban areas (Melosi 2000). However, for efficiency’s sake, sewer lines tend to follow the native watersheds where gravity can do more work than pumps. Thus, while storm and sanitary "sewersheds" may follow the general form of the topography of a city, the sewershed boundaries often deviate from the boundaries of native catchments. Native catchments are modified in another way that affects drainage. Streets and roads, especially those with curbs, alter drainage considerably (Li et al. 1998). Curb drainage is the equivalent of the smallest tributary streams in a native landscape. However, because street construction has as its goal a different function than drainage, and rarely reflects the contours of the land, how surface water is collected and distributed in the metropolis may be as much by accident as by plan. Flow in streams, even in those that for much of their length retain essentially their presettlement form, is affected by the constrictions of bridge abutments, and by the direct addition of drainage water via pipes rather than filtration through soils and ground water (Smith et al. 2005). Sources and sinks of water in the metropolis is a complex pattern reflecting the impact of many kinds of infrastructure. Again, a hybrid structure emerges, combining engineered and native forms. Soil moisture, erosion, and soil vegetation cover are all linked to infrastructural heterogeneity in cities.

Organisms are an important, but sometimes neglected, component of urban ecosystems (Pickett et al. 2001). Both native and naturalized, and invasive exotic plants play important roles in cities and their distributions are heterogeneous (Szlavecz et al. 2006, 2008). Trees and denizens of lawns are the most conspicuous organisms in and around cities. However, mammals, including some that burrow, are also urban residents. Earthworms, soil invertebrates, and litter-dwelling arthropods are significant in soil food webs (Korsos et al. 2002; Pouyat et al. 1994). Invasive organisms, such as vines that inhibit reproduction of native trees (Thompson 1999), or disease vectors and uncontrolled parasites and predators have had major reorganizing effects on urban forests (Nowak et al. 2001). Oriental bittersweet and kudzu are examples of the first kind of exotic, and chestnut blight and the hemlock woolly adelgid are examples of the second. The distribution of organisms is affected by household and organizational management decisions (Hope et al. 2003), proximity to ports and transportation corridors, and response to the built and native physical environment. While many organisms in and around cities are planted or purposefully maintained, most are volunteers that disperse, establish and grow with little direct and intentional human input. Soil dwelling organisms and terrestrial plants have particularly significant effects on soil structure and function. Altered soil food webs may be significant features of urban soils.

The final, and perhaps defining kind of urban heterogeneity is social. The layers of social heterogeneity are many (Grove and Burch 1997; Grove et al. 2003). The basic one is demographic: how many people occupy a given area? What are their ages, sex distribution, ethnic identification, and other aspects of social identity, such as class, education, and life style. The last of these characteristics, lifestyle, is a relatively new one in the arsenal of urban social scientists (Grove et al. 2005). It recognizes that in the post-industrial metropolis, consumption of goods and services may be a more crucial determinant of social processes than the production and distribution functions that defined the industrial metropolis. Indeed, many of the standard demographic measures are appropriate to understanding labor and production capacities of the city. The new theory of life style identity may be more appropriate to an urban world that is no longer focused on the accumulation of raw materials, the production of manufactured goods, and their distribution (Grove et al. 2006). Hence, in addition to the familiar demographic layers of heterogeneity, new lifestyle-based ones now help to understand the city. This heterogeneity accounts for purchasing decisions, leisure activities, and identity as a part of a far flung social network, rather than a local network of face to face interactions in the neighborhood or workplace.

The soil impacts of this shift are seen in the programs aimed at decontaminating soils of brownfield sites. Indeed, the desire to convert abandoned port facilities or industrial sites to upscale residential properties or to parks, suggests different roles and standards for the soils in those sites. Change in soil structure and function is proceeding apace in post-industrial sites in many cities.

Access to capital is an important social heterogeneity. Capital includes not only cash and assets, but access to social power and support networks (Costanza et al. 2002; Gottdiener and Hutchison 2000). These are based on income, but also on education and training, capacity to organize for political purposes, and entree into political power structures. These kinds of social and human capital are distributed heterogeneously across a metropolis. They can influence what damaged soils are restored, where soils are impacted by new vegetation establishment, or where green space is maintained or established.

Institutions are a final kind of social heterogeneity. Institutions can be formal or informal, persistent or fleeting, and focused locally or more broadly, including regional to global concerns (Machlis et al. 1997). They can reflect proximity, as in a community group, or can represent a far flung network of people who rarely or never meet face to face. Institutions control and influence territory, and establish property regimes. Property regimes are the patterns of ownership, tenancy, and control of land use (Grove 1995). Property regimes range from the uncontrolled "open access," to community control of a commons, to state control, and finally to private control, whether by individuals, households, or organizations. The status of soil on a parcel of land can depend on the property regime (Grove et al. 2006).

Section summary: Effects of heterogeneities on soils We have outlined the kinds of heterogeneity that can exist in urban systems. This variety is impressive, but our review is necessarily selective. Yet, it is clear that even an incomplete listing of heterogeneity has many links to urban soils. First, climate heterogeneity affects where atmospheric deposition to soils will be high, and where low, where soil processes will be limited by water and temperature, and where those processes will be facilitated by climatic factors. Climate also affects where pollutants will concentrate. For example, prevailing winds, coupled with the lag in generating O_3 from precursors yields higher concentrations of ozone in suburban Long Island rather than in New York City (Gregg et al. 2003). In contrast, patterns of nitrogen deposition (Lovett et al. 2000) is driven more by the proximity to New York City due to traffic and road density (Medley et al. 1995). Second, land cover and topography determine where soil forming processes may proceed essentially as they did before settlement, as opposed to where soil formation will be stopped, or will start anew with the deposition of new parent material, or the burying of formerly surficial horizons. The massive engineered changes to topography alter drainage and hence the availability of water as a soil erosion, leaching, and weathering driver. The altered maintenance of native topography also determines where vegetation and litter deposition can continue to play a major role in soils versus where they will be reduced. Third, infrastructure alters local drainage patterns, and adds or removes water from specific urban patches. Transportation corridors and the management of storm and drinking water, and the handling and treatment of sewage can affect soil water and soil nutrients. Septic systems versus sanitary sewer systems have different loadings of N to soils and streams. The flows of water between supply mains, storm drains, sanitary sewers, and ground water are key exchanges that affect urban soils. Organismal heterogeneity determines where new invasives will alter soil structure, reducing or enhancing soil erosion, and influencing the ability of soils to retain nitrogen and other important nutrients. The interaction among organisms determines where tree canopies will persist, what species those canopies will be made up of, and how the understories of urban forests can participate in nutrient processing and maintenance of biodiversity. The fact that the timing of growth and activity in exotic species is often extended compared to natives is important to urban soil function (Pickett et al. 2008).

Integrating altered resources, disturbance and heterogeneity

Patch dynamics is an ecological concept that can integrate the various kinds and effects of heterogeneity on soils in and around cities. Patch dynamics recognizes the role of heterogeneity in human settlements (Pickett et al. 2005). This concept posits that spatial heterogeneity can be represented as patches, sometimes with soft boundaries. Patches differ from one another in some feature or characteristic that is, in the aggregate, homogeneous within each patch. Patches defined by contrasts in one characteristic may be internally heterogeneous in a different characteristic. In a model where patches have soft boundaries and are quite small, the formal representation of heterogeneity may be better presented as a surface or field. It is important that the individual patches in a mosaic can change shape and content. Hence, the concept also recognizes the dynamics of that patchiness.

In the case of urban areas, there may be several layers of patchiness, as we have illustrated above. The patches represented in each layer may interact. For example, the type and density of vegetation in public rights of way is affected by the lifestyle characteristics and property regimes of various neighborhoods (Grove et al. 2006). Similarly, the nitrogen yield in small watersheds is predicted by a patch classification that combines built and vegetated components (Cadenasso et al. 2006). Hence, linkages between layers of heterogeneity exist. Linkages may not occur instantaneously. For example, the correlation between the tree cover in neighborhoods in 1990 reflects the social characteristics as represented by the 1970 census in the same areas (Grove 1996). This correlation suggests a lag between social change and vegetation change. There is the possibility that feedbacks between such layers exist as well, as vegetation status is a component of neighborhood desirability in some cases (Troy et al. 2007). Thus, the patchiness in soils and their function is affected by patchiness in other features of the city, and as the patchiness of state factors changes, the soils pattern and processes are expected to change as well, though perhaps involving a time lag.

The general model that emerges from this discussion of urban heterogeneities is one of altered resources, multiple kinds and regimes of disturbance, and diverse, interacting layers of spatial heterogeneity. Biophysical and social layers interact to define the heterogeneity of urban systems, including native or remnant aspects of heterogeneity and novel, engineered and accidental human caused heterogeneity. In this complex matrix, ecological processes continue. Water regulation, nutrient processing and retention, vegetation invasion, and plant succession are all still aspects of the city. Soils are a part of these urban ecosystems, and exist in both essentially native and in highly modified or engineered forms (Effland and Pouyat 1997). The urban area is a hybrid ecosystem consisting of constructed, social, biotic, and physical components. Soils—both anthropogenic and native—remain an important ingredient in, reflection of, and response to urban heterogeneity. The implications of this theoretical stance are (1) to support for inclusive classifications of soils and urban systems in general, that reflect the complexity of urban factors that shape and modify soils (e.g. Effland and Pouyat 1997); (2) to recognize the complex ecological, bio-physical, and socio-economic factors that interact to directly and indirectly modify urban soils; (3) to suggest a layered, spatial model of patchiness and change in urban soils and the state factors; and (4) to represent the place of soils in the feedbacks of urban systems that appear in dynamic patchworks. Research hypotheses following this view should examine not only the proximal changes in physical and biological drivers, but also distal socio-economic drivers for those biophysical changes in urban systems. It is these more distal social factors that differentiate soil formation in urban and non-urban systems.

A common framework for urban and non-urban soils

We suggest a common framework that applies to both urban and non-urban soils. Following Effland and Pouyat (1997) we have accepted the usefulness of Jenny's (1941) state factor approach to soil formation. We have described the important role of social processes and institutions in forming and altering urban soils. Linking social and biophysical drivers has become a powerful concern for ecology in general. Thus the framework for understanding urban soils emphasizes the same features as are driving urban ecological and landscape ecological processes in general: the importance of spatial heterogeneity of the social and biophysical disturbances and spatial patterns of resource alterations. The framework we present builds on prior advances in urban soil science. Effland and Pouyat (1997) emphasized the creation of new parent material and the resetting of the soil formation process in urban systems. In contrast, because the five state factors interact, this paper has emphasized the modification of all five soil forming factors by humans in urban areas. The elements of urban heterogeneity are the same kinds of things that led to the creation of the state factor approach to soils: climate, landform, parent material, organisms, and time. In order to translate this familiar scheme to metropolitan systems two things must be done. First, it must be applied at finer scales than the continental origin of the concept. This is because the scale of heterogeneity in urban landscapes is often quite fine. Second, the sequences used to discover and articulate the soil forming factors at regional and continental scales are best seen as complex spatial mosaics in settled systems. A key to the application of the framework is the fact that so much of the heterogeneity in urban areas reflects grids and regular patterns of development based on property parcels, and combines both built and native components that vary at different rates. Consequently, sequences of climate, or parent material, or organisms, and so on, may have to be modeled as abstract gradients rather than literal transects as they were in the early application of the state factor approach.

The framework we have sketched has four components, which can be represented graphically. First is a conception of the nature of ecological events, particularly disturbance (Table 1). Second is a scheme for translating the state factor approach to urban systems by incorporating specific mechanisms that are especially important in urban systems (Fig. 1). Third is a human ecosystem framework, which specifies the kinds of social structures and interactions that influence the physical, ecological, and social mechanisms (Fig. 2) that contribute to the state factor approach. Finally, a view of how the current framework builds on the precedent frameworks for soil development emerges (Fig. 3). We summarize the key concepts and components of our integrated framework below.

The events which can affect the structure of any ecological system, and of soils in particular, have several universal features. We focus on events rather than aggregate phenomena (cf. Bart and Hartman 2000) in order to be able to tease apart the specific interactions, actions, and mechanisms that control soil formation. We have emphasized the role of disturbance in this paper. As an event that alters the structure of a system,

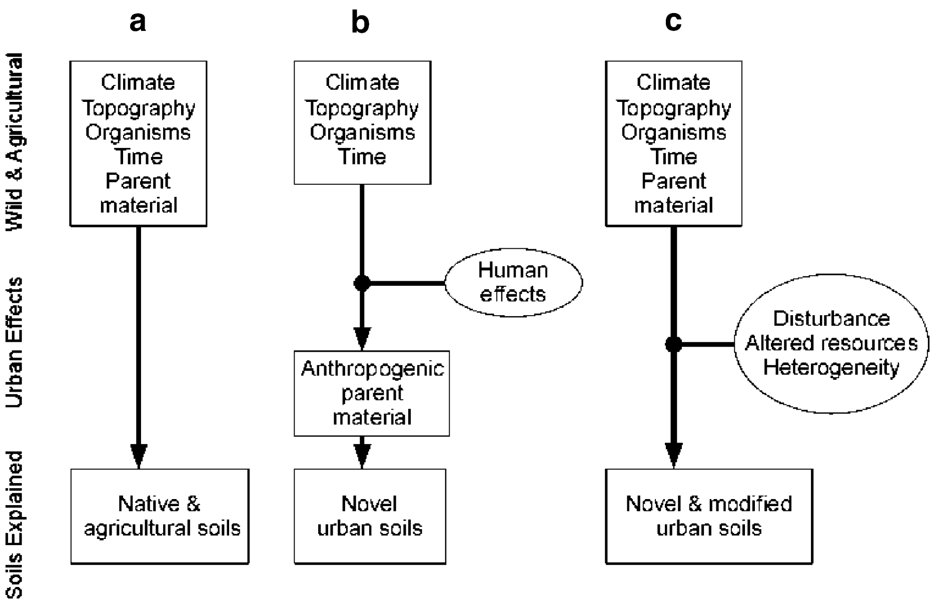

Fig. 3 A comparison of frameworks for the formation of soils, and their relationship to urban conditions. *Columns* represent different frameworks for relating state factors, while rows indicate how human factors are incorporated into each framework. **a** The *left hand column* summarizes the state factors identified by Jenny (1941), which were identified to explain the formation and variation of native and agricultural soils. **b** The *middle column* summarizes the extension of the state factor approach to urban systems made by Effland and Pouyat (1997). This version of a soil formation framework emphasizes the role of new or modified parent materials in the formation and classification of novel urban soils. **c** The *right hand column* summarizes the comprehensive approach to a framework taken in this paper. It emphasizes that each of the five state factors may be affected by human actions and structures in urban ecosystems. These human actions can be evaluated as physical disturbances, altered resource availability, and spatial heterogeneity. The interactions of the five state factors with the three anthropogenic filters yield new urban soils, or modify existing soils in urban systems. *Lines ending in dots* indicate where human agency acts in a particular framework. In **b**, the *arrow between the wild and agricultural state factors and anthropogenic parent material* should be read as "acts on" while the *arrow connecting the parent material and the novel soils box* should be read as "results in." All *other arrows* should be read as "results in"

disturbance is an event that has (1) sudden onset, (2) short duration, and (3) may have persistent or transient effect. Ecological events may have a variety of features of onset, duration, and effect (Table 1). Disturbance affects structure, while stress affects function. Pulse events include disturbances, but may also include stresses. Press events include structural modifications that are persistent. The important message here is that the kinds of events that can affect soils in urban areas in fact have a wider variety of characteristics than have been included in the concept of disturbance. This suggests a very rich array of ways in which to construct models of how urban environments can affect soils (Table 1).

The second component of our framework is the translation of the state factor approach to urban systems. As mentioned before, we have shown possible or actual ways in which all five of the state factors can be altered in urban systems, and hence can affect urban soils (Fig. 1). Many of the mechanisms and scenarios we have presented are in fact hypotheses. However, presenting what is possible as a stimulus for testing hypotheses and promoting model building is a key role of causal frameworks of the sort we present (cf. Cadenasso et al. 2003).

The human ecosystem framework shows the place of soils in urban systems, and identifies the general kinds of social causes that can influence soils both directly and indirectly. The important point here is that soils are a part of a complex, coupled natural-human ecosystem, and that understanding how urban areas affect soils requires understanding which of the socio-economic drivers are in play in a particular situation. Furthermore, whether and how soils feed back to social perceptions, behaviors, and organizations is a key research concern in urban ecosystems (Grimm et al. 2000; Collins et al. 2000). The features of the human ecosystem are the agents and constraints on disturbance, resource alteration, and spatial heterogeneity.

Putting these three conceptual components together yields a comprehensive framework for urban soil research. It accepts the five state factors as the crucial, interacting causes of soil formation that must operate in urban systems as they do in non-urban situations. It adds the components of the human ecosystem as the mechanisms that cause disturbance, altered resources, and spatial heterogeneity. These are the filters that affect how the five state factors operate in urban situations. Finally, the comprehensive framework indicates that the concern in urban systems is with both novel and modified soils (Fig. 3). Of course, there may be some native soils in urban systems that are relatively little modified. However, the fact that urban environments are beginning to affect even rather distant areas suggests that modification is a safer initial assumption for native soils in urban areas. The ecological functions of all these sorts of soils requires increased attention as more and more of the world's human population moves to cities, and converts the land it occupies and even affects soils at a distance.

In conclusion, we find that the state factor approach from classical soil science is an adequate foundation for understanding and framing predictions about urban soils (Fig. 3a). Building a framework for urban soil processes on this classic foundation will also permit ready comparison of the nature and functioning of urban and non-urban soils. The state factor approach must, however, be altered to specify uniquely urban combinations of factors and structures (Fig. 1) that can affect soil formation (Fig. 3b,c). Effland and Pouyat (1997) expanded the state factor approach based on the fact that new or highly modified parent materials are clearly important in urban ecosystems. We have emphasized that urban modifications can also affect the remaining state factors as well. To build a comprehensive framework for the development and functioning of urban soils, we note that the human factor operates in subtle ways that go beyond the obvious density of the population, or the classical land cover types that exist in and around cities (McDonnell and Pickett 1990). The human dimension or factor must account for human capital, social capital, and built capital. In particular, the role of small and large, formal and informal, persistent and transient institutions must be accounted for. Institutions manage property, and so different property regimes must be accommodated in the anthropogenic factor.

The framework we present suggests that the classical state factors of Jenny (1941) can each be modified by anthropogenic processes in cities and metropolitan areas. The state factors therefore operate in urban systems through a set of filters (Fig. 3c). The first filter is altered resources and stress factors. Resource use can be affected both by the amount of resources present, and by stress factors that constrain how those resources can be used. Disturbances, for which we follow the rigorous definition from mainstream ecology, as events that alter the system structure, are the second anthropogenic filter affecting the state factors. Disturbances have the potential to subsequently affect resources and stress factors. Finally, heterogeneity, the spatially explicit arrangements of human factors, the built and engineered environment, and the native and introduced organisms in the urban matrix is the third filter. Together with the five state factors, the three kinds of anthropogenic filters provide a framework to advance the study of urban soils, and to promote comparison of urban with non-urban soils. The state factors and the filters at work in urban systems are shared with non-urban systems in kind, though not degree. The complex interactions embodied in this new version of the state factor framework can be useful to ecology is it attempts to integrate social processes into its models of ecosystem structure and function.

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