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Commentary

COMMENTARY

The state factor model and urban forest restoration

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Abstract

A ‘state factor’ model of ecosystems can serve as a conceptual framework for researching and managing urban ecosystems. This approach provides alternative goals and narratives to those derived from historically grounded dichotomies between nature and culture, which can reify constructions of human influence as inherently destructive. The integration of human behaviour and state factors is critical to the application of a state factor model to urban ecosystems. We emphasize the role of culture in co-producing urban ecosystems and the importance of feedbacks between urban ecosystems and state factors. We advocate for ecosystem models that encourage local agency and actions that enhance the capacity of cities to constructively adapt to environmental change. We contrast this approach to efforts intended to minimize human impacts on ecosystems. The usefulness of the state factor model for informing such efforts is assessed through a consideration of the norms and practices of urban forest restoration in New York City. Despite the limitations and challenges of applying a state factor model to urban ecosystems, it can inform comparative research within and between cities and offers an intuitive framework for understanding the ecological conditions created in cities by human behaviour.

Key words: urban ecosystems, ecological restoration, urban soil, urban forest

Optimizing urban ecosystems

As anthropogenic changes to the earth’s biomes escalate, the attention of ecologists has expanded from the study of natural and rural systems to include the ecology of cities. This is not only due to the growing size, impact and importance of cities but also due to the recognition that cities offer insight into the ecosystems of the future (Pickett et al. 2011). Hotter, more crowded and more thoroughly structured by humans than surrounding landscapes, the distinctive characteristics of cities are remarkably different from natural systems, yet ecologists have made substantial progress investigating biological processes within cities, and in characterizing cities as urban ecosystems (McPhearson et al. 2016). Despite the altered patterns and processes of urban landscapes, researchers have discovered high levels of ecosystem function and biodiversity (Faeth, Bang, and Saari 2011; Pickett et al. 2011). These findings imply a potential to intentionally integrate natural processes into cities, in order to improve ecosystem function, quality of life and the conservation of biodiversity.

Even as the trends of urbanization, extinction and environmental change have created an imperative to protect and restore nature in cities, the relevance of natural references to guide the redesign and management of ecosystems, particularly urban ecosystems, has been called into question (Hobbs et al., 2009; Standish, Hobbs, and Miller 2013). Despite this, natural references (by which we mean historic ecosystems or ecosystems considered less altered by human activity) not only function as target ecosystems for ecological restoration (McDonald et al. 2016), they serve as functional analogues for designers (Beck 2013; Strain et al. 2018), points of comparison for research into anthropogenic environmental change (McDonnell and Hahs 2009) and influence the cultural valuation of natural areas in cities (Maraja, Barkmann, and Tscharntke 2016). Preferences for historic or idealized landscapes, whether the English countryside (Ignatieva and Stewart 2009), the African savannah (Falk and Balling 2010) or an imaginary primeval forest (Denevan 1992) may be misleading models for urban landscapes. Fidelity to these models can circumscribe the ability of cities to adapt to environmental change through ecosystem stewardship (Chapin et al. 2010) re-engineering ecosystem function and the incorporation of novel communities to enhance ecosystem function and resilience (Collier 2015).

A transition to more sustainable human-dominated landscapes will require the widespread application of ecological knowledge to practical decisions in the face of uncertainty and rapid change (Kato and Ahern 2008). Models of urban ecosystems will need to include decision-makers in any coherent framework (Alberti et al. 2003). The growing recognition of the human role in co-producing (Rademacher, Cadenasso, and Pickett 2019) urban ecosystems may provoke a significant reconsideration of the values and normative principles that guide decision-making, including shared notions of what constitutes nature in the city. High-resolution mechanistic modelling of such a complex, dynamic and recursive system is unlikely to reliably inform decision-making or offer confident predictions of ecosystem responses to social and environmental changes (Chen, Chen, and Fath 2014).

We propose that the state factor model of ecosystems, an experimental framework that has emerged from soil science, could be used to understand cities in relation to a small set of dynamic factors. Such an approach offers a relatively simple way to analyse the needs and possibilities of cities, expressed in terms of the familiar processes that shape any landscape and can complement research into the complex socio–ecological interactions that drive urban and other human-dominated ecosystems (Chowdhury et al. 2011; Burch et al. 2017; Roman et al. 2018). Critically, it emphasizes the human role in establishing the conditions for the biological components of urban ecosystems, thereby encouraging collective responsibility for, and engagement with nature in cities. To explore what this approach implies for an applied discipline, in a specific ecosystem, we consider urban forest restoration in New York City as an example.

Managing New York City's forests

In our discussion of urban forests, we refer to areas of any size where natural regeneration of woody species can occur and there is no regular maintenance activity or disturbance that limits the establishment of woody species (e.g. lawn care, regular burning, dumping, etc.). Our discussion of management and policy is focused on urban forests on public lands. Within New York City, there are 4281 ha of forests designated as natural, including examples of mature coastal oak–hickory forests, oak–tulip tree forests, forested wetlands, maritime forests and a wide variety of successional hardwood forests (Pregitzer et al. 2019). These forests have diverse histories of human influence and include remnant and restored forests as well as sites dominated by invasive vegetation. In 2015, New York City's Natural Area Conservancy initiated a process to articulate the values and functional goals that underpin the restoration and management of natural resources in the city (Natural Areas Conservancy 2016). This process, and an effective history of pragmatic, adaptive approaches to forest restoration, may instigate a shift in management practices in New York City, from a reliance on targets of native forest vegetation, towards functional goals. However, in practice, native vegetation remains a proxy for a range of ecosystem properties and has come to represent values that may transcend any specific functional goal prevent the deployment of trait-based models developed to achieve functional targets (Laughlin 2014).

Guidelines for forest restoration in New York City, formalized by the New York City Department of Parks and Recreation (the agency responsible for the management of most of New York City's forests) state that 'the primary goal of urban forest restoration is to return forest structure, process and composition to woodlands and forested areas to within a natural range and thereby create self-sustaining ecosystems' (Bounds et al. 2014). This emphasis on native vegetation was codified by a local city law in 2013, requiring city owned property to minimize the use of exotic vegetation. Natural Area Conservancy's Forest Management Framework (Pregitzer et al. 2018) updates the forest restoration guidelines and continues to prioritize the goal of forest dominated by native species, defining forest 'health' and 'threat' by relative levels of native and exotic vegetation, respectively. The framework estimates a cost between $6078 and $42 076/acre to restore threatened forest and alter successional trajectories towards native vegetative assemblages (Pregitzer et al. 2018, 2019). This projection of the investment required to maintain native forest vegetation highlights contradictions between the goals of self-sustaining ecosystems and maintaining historic vegetation associations. Urban afforestation or the creation of new forests on previously un-forested or altered land provokes further questions about the application of a restoration framework with a strict reliance on native vegetation for the design of urban forests (Hallett 2013).

As part of an effort to integrate social and ecological research on New York City's forests, researchers and mangers were interviewed to develop a shared cognitive model of a healthy upland forest (Johnson et al. 2019). This process confirmed the central role of native vegetation in the conception of a healthy forest and the contested role of human influence on urban forests. Notably, the definition of ecological health did not correlate with how forests were perceived by park users, suggesting that the social value of urban forests may diverge from conceptions of forests maintained in the professional networks that can drive policy (Johnson et al. 2019). The conceptual framing of nature and novel ecosystems has been identified as problem for developing effective governmental response to environmental change (Clement and Standish 2018). Given the importance of 'urban tree professionals' (Roman et al. 2018), in defining and co-producing (Ogden et al. 2019) urban forests, critical engagement with assumptions in the ecological tradition about nature and human influence can illuminate the historical underpinnings of the 'ecological health' of urban forests. This work is important to avoid naturalizing (Robins 2013) the cultural positions of forest professionals as they engage in the critical work of articulating shared values to guide urban forest management and restoration.

The persistence of nature

In 1800, on a scientific exploration of the 'New World', Alexander Von Humboldt described in his journals how deforestation surrounding colonial plantations could lead to changes in soil moisture, erosion and climate. He describes anthropogenic deforestation as ecological 'devastation' with predictable natural, social and economic consequences. Even before the science of ecology was named (by one of Humboldt's many influential admirer's, Ernst Haeckel), Humboldt's early ecological insights captured the complex interdependence of the environment and human development (Wulf 2015). Humboldt articulated a fraught relationship between the collective human activity and the natural world that persists today. With his recognition of our dependence on natural processes, Humboldt initiated what Darwin and others continued, a profound integration of the human and natural spheres, changing a long held European idea that the human and natural orders are fundamentally distinct. Darwinian evolution made 'the age-old belief in nature's separateness untenable once and for all' (Marx 2008). This conceptual unification placed humanity and nature in the same field but in destructive opposition. George Perkins Marsh (1864) expanded Humboldt's insights on deforestation in 'Man and Nature: or Physical Geography as Modified by Human Action'. Marsh developed the argument that damage to vegetation and soil could ultimately lead to the collapse of a society. His empirically grounded arguments for the negative economic consequences of deforestation became central to the growing conservation movement (Wulf 2015). Marsh also recognized the potential for ecological restoration and sustainable development implied by his work, proposing a mode of colonial development where settlers act as a 'co-worker with nature' (Marsh 1864).

Though scientific discourse often avoids the ambiguity of the word 'nature', this contradiction between connection and destruction, demonstrated in Humboldt's observations of deforestation and shaped by European colonialism, continues to affect scientific inquiry. Despite current advances in conceptual models of urban ecosystems, the legacy of traditional ecological thought structures many of the methods and discourses in urban ecology. Forman (2016) argues that ecology would have developed differently had cities been studied as the science developed. A review of urban ecological literature indicated that human activity is regularly conflated with ecological disturbance (Grimm et al. 2017). While some natural scientists continue to look for and characterize human influence on natural systems, fundamentally treating humans as a disruptive force, urban research in the traditions of political ecology, urban metabolism and urban ecosystem science are working towards an integrated understanding of socio–ecological dynamics in cities (Pincetl 2012).

In USA, the concept of nature that coincided with the conquest of the west has been described as a 'sentimental, quasi-religious cult of nature' that 'helped to vent the pathos aroused by the spectacle of ravaged forests, slaughtered bison and "vanishing Americans"'(Marx 2008). This view of nature was shaped by a vision of primal wilderness unspoiled by humanity, a vision that largely ignored the role Native Americans played in shaping the landscape. Although in the 1970s the word 'environment' began to replace 'nature' and carried a greater sense of interdependence (Marx 2008), the mythic notion of a wilderness free of human influence continues to colour our expectations of the landscape. In the ecological understanding of the destructive capacity of humanity, and the sentimental notion of wilderness, nature is defined as qualitatively different, remote and external to the human. The natural order thus conceived may be accessible to the individual but remains distinct and distant from civilization.

In the contemporary urban landscape, the distance between nature and civilization has collapsed, and while one may find meaning in notions of nature as qualitatively different from the human, managing urban ecosystems requires a reckoning with a natural order substantially constituted by collective human behaviour, something that remains deeply at odds with American traditions. This tension can be seen in the discourse of restoration and forest management in New York City which fundamentally aims to undo human influence.

The immediacy and intensity of human influence on urban ecosystems can be illustrated by the 'Sunday effect'. Among the many anthropogenic rhythms that interact with natural cycles, researchers have identified a weekly signal in storm and rainfall patterns down-wind of cities (Cerveny and Balling, 1998). Though there is debate about the extent of this effect (Schultz et al. 2007; Bell and Rosenfeld 2008), research suggests that on a regional scale, precipitation can be driven by aerosols that correlate with traffic patterns. Though plausible mechanisms for this pattern are straightforward, the recognition that our collective agreement to drive during the work week can lead to rainier weekends reveals the degree to which culture does not simply disrupt nature but rewrites its patterns.

While the anthropological literature has different definitions of culture, with different positions on the inclusion of human behaviour, social systems and external material conditions (Beldo 2010), we use 'culture' to refer to the set of symbolic meanings and norms shared by a group of people. We employ culture, as developed by Bourdieu (1993) who defines the field of cultural production, as including both subjective, symbolic systems and external socio–political structures. In particular, we think Bourdieu's distinction between the cultural field and 'habitus' or the dispositions that shape behaviour is particularly useful for our consideration of forest management norms and practices. Following Crane (2010), we acknowledge that culture does not need to be included in an ecosystem model but emphasize that cultural variation and change will nonetheless affect the application of ecosystem models and the trajectories of ecosystems. Therefore, we approach the state factor model as a way to understand the capacity of behaviour to shape internal ecosystem dynamics (such rainfall patterns), and to alter the state factors, through mechanisms such as reducing the emissions of greenhouse gasses. As an example of culture and ecosystem interaction, we focus on the norms that guide city policy towards forest management, and how the state factor model, itself a cultural artefact, can suggest alternative management actions.

Efforts to intentionally manage nature in urban ecosystems can evoke McKibben's (1989) vision of a 'post-natural', managed world, a world where there is nothing 'outside' the human. However, the salient feature of urban ecosystems may not be the ubiquity of our impact on global ecosystems, and an alienation from nature, but an increasingly direct correspondence between the field of culture and the biophysical order. Critical to the development of more sustainable urban ecosystems is the recognition of the ecosystem context and consequences of culture. The state factor model provides obvious points of contact between human behaviour and ecosystems, demonstrating how culture determines the biological conditions within cities.

Interventions in the urban ecosystem, ranging from the development of green infrastructure to the management of remnant forests involve assumptions about human influence and the value of natural systems. By integrating human influence with the other factors that structure ecosystems—time, topography, geology (or parent material) and the pool of potential organisms, the state factor approach can help us overcome the persistent cultural oppositions between nature and culture to develop an understanding of nature consistent with Humboldt's integrated vision of the world, but one that facilitates urgent and constructive human action. If we accept deforestation as a foundational parable of ecology, one that established distance and conflict between humans and nature, forest restoration, developed in a forward-looking framework offers a parable of urban ecology that articulates an understanding of nature less divorced from collective human endeavour.

Soil and the state factor model of ecosystems

The state factor model has been used to guide research into soils in a range of landscapes since the model of soil formation was developed by Doukachev in 1879. Formalized as an equation (Jenny 1941), the remarkably short list of factors found to control soil formation can also be used to predict the state of any terrestrial ecosystem (Jenny 1961; Amundson and Jenny 1997)

$$S = f(cl, o, r, p, t, \ldots), \tag{1}$$

where soil (*S*) represents as a function of climate (*cl*), biota (*o*), topography (*r*) and time (*t*) (Jenny 1941). The ellipses indicate the potential need for additional factors. Extended to ecosystems (Amundson and Jenny 1997), soil (*S*) is replaced with 'Ecosystem Properties'.

Although researchers have found it necessary to add factors, or acknowledge complicating stochastic processes (Groffman et al. 2004) in various settings, this model has been effectively used to identify natural experiments and guide comparative ecosystem research. If one state factor varies and the others remain relatively constant, changes in an ecosystem can be ascribed to the influence of the variable factor. This method allows for the identification of natural experiments and could inform experimental manipulations in urban ecosystems. One example is 'chronosequences', in which the length of time soil-forming factors have been operating on a comparable landscape varies. Chronosequences have been used to explore how ecosystems evolve over time, including how forest soils develop following human-caused disturbance (Yesilonis et al. 2016) and within urban ecosystems (Setälä et al. 2016). Similar natural experiments can be found for the other state factors. Theoretically, the state factor model applies to all terrestrial ecosystems, however, the relationships represented by the model are derived from historical patterns, and how these relationships hold up to environmental changes and the unique characteristics of human-dominated ecosystems will affect its usefulness as a predictive tool.

Although the state factor model does not explain in detail how the soil-forming factors control ecosystems, it is no coincidence that an account of soil formation can also predict ecosystem properties. The model was created to simplify a complex system (soil) in the absence of a well-developed mechanistic model. Through their gradual development, soils link geologic history to recent disturbance and ongoing processes, natural and anthropogenic. Soil functions, such as decomposition, are sensitive to a range of environmental changes, integrating diverse anthropogenic impacts with fundamental ecosystem processes (Carreiro et al. 2009). As the primary site of nutrient uptake by vegetation, soils influence the distribution of biological assemblages (Pastor et al. 1982; Beauregard and De Blois 2014) and, through their development, constrain the future of ecosystems. Restoration ecologists refer to biological information and cumulative influence of recent events as the 'ecological memory' of soils (Schaefer 2011). The legacy of anthropogenic changes to urban soils has so fundamentally shaped urban ecosystems, direct and 'drastic' management of urban soils may be necessary to facilitate ecological restoration in cities (Pavao-Zuckerman 2008). If this management of urban soils is to include local stakeholders, it will require accessible knowledge of urban soils and a shared understanding of the role of soil in ecosystems.

Global enthnopedological research considers indigenous understandings of soil to include land management approaches and symbolic content in addition to specific knowledge about soils (Barrera-Bassols and Zinck 2003). While indigenous understandings of soil are often contrasted with soil science, scientific models include assumptions about the world, function as part of a local culture and inform local land use. The inclusion of human activity allows the state factor model to function as an integrative metaphor (Musacchio 2009), not just for soil and ecosystems, but for humans and nature in cities.

Humans in the state factor model

The inclusion of humans in the state factor model (Jenny 1941; Amundson and Jenny 1991) has guided research into predictable ecosystem responses to different types of human activity, including the influence of agriculture (Jenny 1941; Bidwell and Hole 1965) and urbanization (Pickett and Cadenasso 2009; Pickett et al. 2011). Effland and Pouyat (1997) explicitly identified urban–rural gradient soil studies as potential 'anthroposequences' and employed a state factor equation that includes humans as a soil-forming factor. This approach separated humans from other organisms in the state factor equation due to the scale and intentionality of human impact on soils. Research on anthroposequences using this approach has demonstrated how the human factor can overwhelm natural soil-forming factors, leading to a 'global convergence' of certain urban soil properties (Pouyat et al. 2015) Although this model intentionally isolates human influence in order to study the effects of urbanization, it has not always found such effects to be destructive. In one counter-intuitive example, soil carbon in residential lawns was found to exceed carbon stored in surrounding landscapes (Raciti et al. 2011).

In general, analysis of the 'anthropogenic factor' has shown the importance of land use patterns and management decisions on soil properties (Pouyat et al. 2010). This perspective aligns with research emphasizing the importance of local decision-making in structuring urban forests (Ogden et al. 2019). Local decision-making can lead to both global convergence between cities and increased heterogeneity within urban ecosystems. The potential for local variation and innovation is not captured by employing an 'anthropogenic factor'. The formulation including humans in the state factor model proposed by Amundson and Jenny (1991) in Equation (2) allows for distinctions between exogenous and endogenous cultural dynamics, which can drive qualitatively different forest transitions (Lambin and Meyfroidt 2010). It also represents humans as part of the organism factor and introduces a separate factor for culture.

$$\begin{aligned}&\text{h (human phenotype), c (culture), a (animals), v (vegetation),}\\&\text{s (soils)} = f(\text{o}_{\text{h}} - \text{human gene pool, } \text{c}_{\text{i}} - \text{cultural inheritance,}\\&\text{traditional state factors}: cl, o, r, p, t, \ \ldots)\end{aligned} \tag{2}$$

Equation (2) represents state factor model including humans (Amundson and Jenny 1991). The left side of In Equation (2) is a list of dependent variables describing the ecosystem state, whereas the right side of the equation lists the state factors. Amundson and Jenny (1991) also considered the human ability to function as a master variable, operating with tectonic movements, rates of solar radiation and evolutionary parameters to affect the state factors. In this approach, human influence is distributed throughout the model. This structured representation of human influence acknowledges both the magnitude of human influence and its interaction with multiple levels of the model's conceptual hierarchy. In urban ecosystems, the rate, magnitude and spatial extent of cultural impacts on biophysical processes can be captured by the inclusion of feedbacks (Fig. 1) that operate beyond internal ecosystem dynamics.

The feedbacks in Fig. 1 represent the rapid influence of urban ecosystem state changes on state factors and could include culturally mediated processes, such as intentional management, policy land use decisions as well as indirect environmental impacts. This approach can focus policy towards intentional management of state factors.

The apparent environmental determinism of the state factor model may seem poorly suited to understanding cities and alternative urban ecosystem scenarios. Since the model assumes that an ecosystem state is completely dependent on external factors, it cannot account for variation contingent on local decision-making or divergent ecosystem responses to state factors. However, the state factor model can be compatible with a complex understanding of agency and cultural change. By avoiding the use of a separate anthropogenic factor, and instead using the state factor model to explicate, compare and vary the human impact on the traditional state factors, we can retain a role for agency and use the state factor approach to model and compare alternative ecosystem states and thereby inform decision-making.

State factors and forests in New York City

To illustrate how humans have altered state factors for urban ecosystems and to consider the implications of management geared towards state factor change, we briefly consider what each factor represents and implies for urban forests. The mitigation of human impacts on state factors has been proposed as a general goal for urban restoration (Pavao-Zuckerman 2008).We expand on this goal and identify potential strategies to adapt to state factor changes or intentionally alter state factors. Additionally, we consider how this perspective departs from a reliance on historic references for setting management and restoration targets.

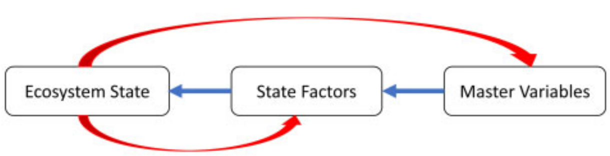

Figure 1: The traditional state factor model (blue arrows) including feedbacks (red arrows).

Climate (*cl*)

New York City is engaged in initiatives to both mitigate and adapt forest restoration practices to a changing climate. Tree planting in the city is motivated by efforts to improve the climate locally and to address global climate change through the reduction in carbon emissions. The cool neighbourhoods initiative is strategically planting trees to mitigate projected increases in the intensity of heat waves and associated health problems. With the development of a heat vulnerability map that incorporates factors such as race and access to healthcare, tree planting can be targeted to maximize the public health outcomes of the localized cooling created by shade and transpiration (Charles-Guzman et al. 2017).

New York City is increasing the planting of native species anticipated to adapt to future climate conditions, through recommendations in the forest management framework (Pregitzer et al. 2018). While this is an example of the shift we advocate for, climate-adapted species palettes will need to move beyond strictly defined native vegetation and historic communities. Urban forests represent unique and powerful opportunities for reducing disequilibrium between climate and forests. While climate is generally understood to determine the historic ranges of tree species at a broad scale, it is uncertain how changing climate conditions, amplified by the urban heat island effect and interacting with urban soils, will impact the forest and associated ecosystem services. Given the slow and ongoing distributional shifts in response to Holocene climate changes (Davis and Shaw 2001), the response of forests to current rates of climate change ensures growing disequilibrium between climate and forest assemblages. Identifying an adaptable sub-set of native species, including species outside their historic range, could support functional redundancy and species diversity within an urban forest, while assisting with species migration (Woodall et al. 2010). This approach would be enhanced by increased study of the structure and function of spontaneous and unmanaged urban assemblages, which are likely to exhibit better adaptation to the urban climate.

Biotic (*o*)

The biotic factor refers to the pool of potential species in an ecosystem. The globalization and de-stabilization of this factor includes an expanding suite of invasive species that continue to change the composition of urban vegetation (Ellis et al. 2010). Invasive earthworms have altered decomposition and nutrient cycling (Szlavecz et al. 2006) and introduced insects and diseases eliminate tree species from the forest (McCullough and Katovich 2015). As with climate, the long-term implications for historic forest associations remain uncertain, but existing management strategies to limit new introductions, rapid response to emerging threats can be understood as mitigating the change to the state factor.

Some of the most outstanding questions of urban ecology relate to the structure and function of spontaneous or intentionally assembled novel communities (Groffman et al. 2017; Pearse et al. 2018). Characterizing the ecosystem services and disservices of unmanaged urban vegetation could provide a critical reference for assessing the costs and benefits of maintaining native forest in relation to a likely alternate ecosystem. The restoration and conservation community has been engaged in a debate regarding the value of novel ecosystems relative to historic or natural references (Corlett 2015). Novel ecosystems can be defined as 'one in which the species composition and/or function have been completely transformed from the historic system. Such a system might be composed almost entirely of species that were not formerly native to the geographic location or that might exhibit different functional properties, or both' (Perring et al. 2013). Research in New York City suggests that in the absence of management, vines and other invasive plants can replace native forest (Johnson and Handel 2016) and create assemblages with remarkably different structures and compositions, approaching such a novel state. While spontaneous vinelands may not be desirable, they need not define the potential for novel communities, which can be sources of ecological resilience (Collier 2015).

Regardless of the relative value of historic or novel communities in an urban context, it is important to avoid the tendency to view one as 'more natural', when they are both shaped by human influence. We suggest most urban forests can be viewed as historic communities on a novel trajectory, determined by the state factors. Attempts to guide this trajectory could be driven by a desire to maintain natural heritage, support ecosystem services or specific conservation goals. A proposed general principle of urban ecology is that most rare native species are 'doomed to local extinction due to concentrated human impacts, whereas rare nonnative species may disappear, persist, or spread' (Forman 2016). Specialist species currently exploiting novel urban niches suggest potential to make significant conservation contributions in the constructed urban environment. Examples such as the smooth cliff brake fern, Pellaea glabella ssp glabella , a rare fern in New York state that has been found growing spontaneously in novel urban topography, including the walls along the heavy traffic of Madison avenue (Taft, 2014), demonstrates the potential for the conservation of forest species as part of constructed novel communities.

Topography (*r*)

While the topography factor may be the most visibly altered urban state factor, the same capacities that allow the construction of cities, create opportunities to re-engineer urban topography for urban forests. In the process of developing cities, streams are buried, wetlands filled and hills leveled (Sprin 1984; Sanderson and Brown 2007). While the climate influences tree distribution on a large scale, topography dictates distribution within a landscape. The loss of natural relief in the landscape has reduced the ecological heterogeneity of the urban forest, though its influence can be seen in older urban forests, most likely to be found on steep slopes or other topographic features that are difficult to develop, e.g. the terminal moraine in New York City (Bounds et al. 2014). While the constructed environment has created a new topography, there is a tremendous opportunity to intentionally re-engineer topography for ecological outcomes. Globally, it is estimated that by 2050 up to 60% of the built environment will be new or rebuilt (Ahern, Cilliers, and Niemelä 2014). In New York City, forest restoration on a novel topography has been pioneered on a large scale in the restoration of Freshkills landfill, formerly the world's largest landfill, into a 890 ha park (almost three times the size of Central Park and the largest park developed in New York City in over 100 years) (New York City Department of Parks and Recreation) Ongoing projects, including efforts to redesign New York City's shoreline in response to rising sea level, should be designed to create functional ecological heterogeneity, including reconceiving of New York City's diminished maritime and wetland forests.

Parent material (*p*)

The constructed environment has also become part of the urban parent material—the materials that our soils are derived from. While the influence of underlying geology and sediments continue to affect soil development, ongoing inputs to soil from the urban environment, including atmospheric deposition, construction debris and litter have established novel pedogenic processes (Effland and Pouyat 1997; Huot, Simonnot, and Morel 2015). These anthropogenic inputs alter soil properties that affect forest health and composition; without a reduction, they are likely to increase divergence from historic or rural references. Characterizing the interactions of urban pedogenesis and forest dynamics remains an important frontier and should inform restoration planning. Work in New York City has contributed to the foundation of this (Pouyat et al. 2010), including an urban soil survey that describes a range of new anthropogenic soil types (New York City Soil Survey Staff 2005) which have been shown to affect native seedling health and growth (Pregitzer, Sonti, and Hallett 2016).

Mitigating changes to parent material on a large scale may not be possible, however, changes to waste management, transportation systems and pollution standards could all be expected to have impacts on this state factor. New York City's clean soil bank, a sediment exchange program, conserves clean soil excavated at depth from construction sites and uses it to cover contaminated soils, supporting the development of parks and gardens (Walsh et al. 2018; Egendorf 2018). Combined with composting of organic material, such a material re-use economy could significantly improve the health of urban soils. The use of constructed 'technosols' (Huot, Simonnot, and Morel 2015) has demonstrated significant promise in remediating severely degraded sites. If sediments derived from native parent material are integrated into new forest restoration projects, they could mitigate the legacy of anthropogenic influences, ironically linking the development of new, taller buildings with an improved outlook for historic forest communities.

Time (*t*)

While the time factor (*t*) is not changed directly by urbanization, the trajectories of urban forests over time have been altered, as has the frequency and nature of the disturbance regime within cities. Studies have found predictable trends in vegetation over time in cities. For example neighbourhoods show a predictable increase and then decline in residential tree cover (Roman et al. 2018). As entire cities age, there tends to be a gradual increase in vegetation species richness (Pickett et al. 2011).

Research in urban forests has also identified a range of contingent, historical legacies that shape urban forests. Ongoing changes to state factors can be expected to alter the re-establishment forests after disturbance, giving each 'time zero' a unique historic signature. For example, changing norms of urban foresters (Roman et al 2018) and an altered pool of species can initiate distinctive successional trajectories. This dynamic, combined with the ongoing loss of urban trees in the USA (Nowak and Greenfield 2018) suggests the importance of preserving existing forests in urban ecosystems. In many regions, the oldest forests can be found in cities, in parks that were set aside from development early in the city's development. For example, some of New York City's most valued forests were established as early as 1800 and serve as exemplars of urban greenspace (Bounds et al. 2014).

Soil development and forest dynamics generally operate on significantly longer time scales than urban land use changes. Allowing time for individual forest patches and urban ecosystems to develop, by developing policy to limit rapid land use changes can be understood as mitigating change to (*t*). A general shift towards early successional species in New York City area forests (Zipperer and Guntenspergen 2009; Pregitzer et al. 2019) also indicates spontaneous adaptation to the urban disturbance regime. Designing afforestation plantings to speed up successional dynamics or artificially rebuild soils may represent useful management adaptations to changes in (*t*).

Do we need a culture factor (*c*)?

In our approach, we consider human behaviour and the results of human activity to be distributed among the traditional state factors. This anthropogenic transformation of the state factors can be understood as a radical externalization of the cultural field, problematizing traditional assumptions and hierarchies ordering subjective meaning and external, material conditions. This approach is compatible with post-humanist theorists who work address the social construction of the human by the urban environment (Grosz 1995). However, as Amundson and Jenny) proposed (Equation 2), an independent state factor to represent culture may be needed in any effort to develop a comprehensive state factor model for urban ecosystems. In Bourdieu's theory, the cultural field operates relatively autonomously from external drivers. Such an understanding of culture may justify introducing an independent cultural factor in order to integrate cultural studies in an ecosystem framework. Research in the USA reveals the degree to which consistent cultural expectations for landscapes drive homogenization in urban ecosystems across distinct biomes (Groffman et al. 2014), while the global homogenization of urban vegetation has been linked to colonialization (La Sorte et al. 2014). Findings such as these suggest that for global comparative studies, a state factor model that treated relatively fixed exogenous cultural drivers as a state factor could be useful.

Whether it is included within the model as a factor or not, the transformation of the traditional state factors demonstrates how culture has shaped the nature of cities. Critical to Bourdieu's theory, the cultural field is subordinate to political and economic power. This insight is important to maintain, when addressing the racial and economic disparities in the distribution of urban forests and ecosystem services (Roman et al. 2018). Recognizing the cultural drivers of urban forests, and their relationship to the social and political order, may help make promote local agency and novel approaches to forest restoration, ensuring institutional fit of management and restoration efforts (Epstein et al. 2015), Local cultural variation and the potentially divergent responses of urban ecosystems should be recognized as a site of cultural innovation and ecological resilience. There is growing body of research demonstrating the variety of cultural meanings found in New York Cities' urban forests (Johnson et al. 2019). The negotiation between local decision-making and broader policy and norms will substantially shape the urban forests of the future. Our approach to culture is intended to allow the state factor model to function as a both an experimental framework and a constructive tool. As an experimental framework, it should inform comparison between cities. Within a city, it should encourage the experimental modification of state factors. As a design guide, altering the state factors can suggest variations on a theme, aiding the design of novel, constructed ecosystems. As a scientific parable that includes and informs culture, we believe that the state factor model can encourage creative, pragmatic and responsible engagement with nature in cities.

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