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Review

Human and biophysical legacies shape contemporary urban forests: A literature synthesis

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ABSTRACT

Understanding how urban forests developed their current patterns of tree canopy cover, species composition, and diversity requires an appreciation of historical legacy effects. However, analyses of current urban forest characteristics are often limited to contemporary socioeconomic factors, overlooking the role of history. The institutions, human communities, and biophysical conditions of cities change over time, creating layers of legacies on the landscape, shifting urban forests through complex interactive processes and feedbacks. Urban green spaces and planted trees can persist long after their establishment, meaning that today's mature canopy reflects conditions and decisions from many years prior. In this synthesis article, we discuss some of the major historical human and biophysical drivers and associated legacy effects expressed in present urban forest patterns, highlighting examples in the United States and Canada. The bioregional context – native biome, climate, topography, initial vegetation, and pre-urbanization land use – represents the initial conditions in which a city established and grew, and this context influences how legacy effects unfold. Human drivers of legacy effects can reflect specific historical periods: colonial histories related to the symbolism of certain species, and the urban parks and civic beautification movements. Other human drivers include phenomena that cut across time periods such as neighborhood urban form and socioeconomic change. Biophysical legacy effects include the consequences of past disturbances such as extreme weather events and pest and disease outbreaks. Urban tree professionals play a major role in many legacy effects by mediating the interactions and feedbacks between biophysical and human drivers. We emphasize the importance of historical perspectives to understand past

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drivers that have produced current urban forest patterns, and call for interdisciplinary and mixed methods research to unpack the mechanisms of long-term urban forest change at intra- and inter-city scales.

1. Introduction

Urban forests encompass trees in cities, towns and suburbs, including trees on private and public lands, from individual street and yard trees to parks and wooded fragments (Nowak et al., 2001; Konijnendijk et al., 2006). These urban forest systems are embedded within a socially and physically complex space; as Kostof (1991) argued, “cities are the most complicated artifact we have created” (335). Cities have been inhabited for centuries to millennia, leaving imprints of human and ecological histories on current vegetation and land cover (Nassauer and Raskin, 2014; Eisenman, 2016, McBride, 2017). Although trees have been planted in human settlements for thousands of years, they were not a prominent feature of cities prior to the mid-1800s (Lawrence, 2006). Therefore the creation of extensive urban forest systems is a relatively recent development in human and ecological history. Urban tree species assemblages can be viewed as novel or designed ecosystems (Higgs, 2016) that arose through past human actions.

However, historical context is often missing from geospatial analyses of contemporary urban tree canopy, composition, and diversity. Such analyses generally associate urban forest characteristics with current conditions in human systems, especially socioeconomic data (e.g., Hope et al., 2003, Kinzig et al., 2005; Avolio et al., 2015a; Schwarz et al., 2015; Gerrish and Watkins, 2018; Watkins and Gerrish, 2018; Avolio et al. *in press*). Although statistical associations between contemporary tree cover, wealth and race illuminate patterns, they do not fully reveal the underlying processes and causal mechanisms (Schwarz et al., 2015). Furthermore, when those associations are limited to present-day characteristics of the human system, they do not account for the lag time between tree planting and maturation. Trees are fundamentally long-lived organisms that require decades to achieve mature size. Indeed, current vegetation cover can be predicted by socioeconomic data from several decades prior (Boone et al., 2010; Grove et al., 2014), suggesting an imprint of past residents on current urban forest patterns. This is a time-lagged interaction (Steen-Adams et al., 2015) due to biological realities of slow tree growth. The communities and institutions that manage urban forests change over time, yielding trees and green spaces as products of earlier decisions.

Yet city trees are more than sociocultural artifacts. Indeed, urban trees have basic ecological requirements of light, water, and nutrients, and they are vulnerable to pests, diseases, and extreme weather. Professional arborists and municipal foresters manage urban forests for those needs and vulnerabilities through planting, maintenance, and removal (Miller et al., 2015). These tree professionals are key actors whose management choices can be seen decades later. Tree planting decisions can be influenced by aesthetic and cultural preferences as well as practical considerations, such as nursery availability and species' tolerances to urban stresses; these factors contributed to the limited species palette deemed suitable for past street tree plantings in many cities, leading to monocultures (Richards, 1983; Pincetl et al., 2013; Campanella, 2003; Lawrence, 2006; Jonnes, 2016). Such monocultures were then vulnerable to pests and diseases, and the history of outbreaks has led municipal arborists to emphasize diversity in planting palettes (Raupp et al., 2006, Hauer and Peterson, 2016). Each step in this functionally contingent series of events can substantially alter urban forests, with human and biophysical drivers interacting across decades. Researchers in urban ecology and urban forestry have stressed the integrated nature of urban ecosystems and the importance of social-

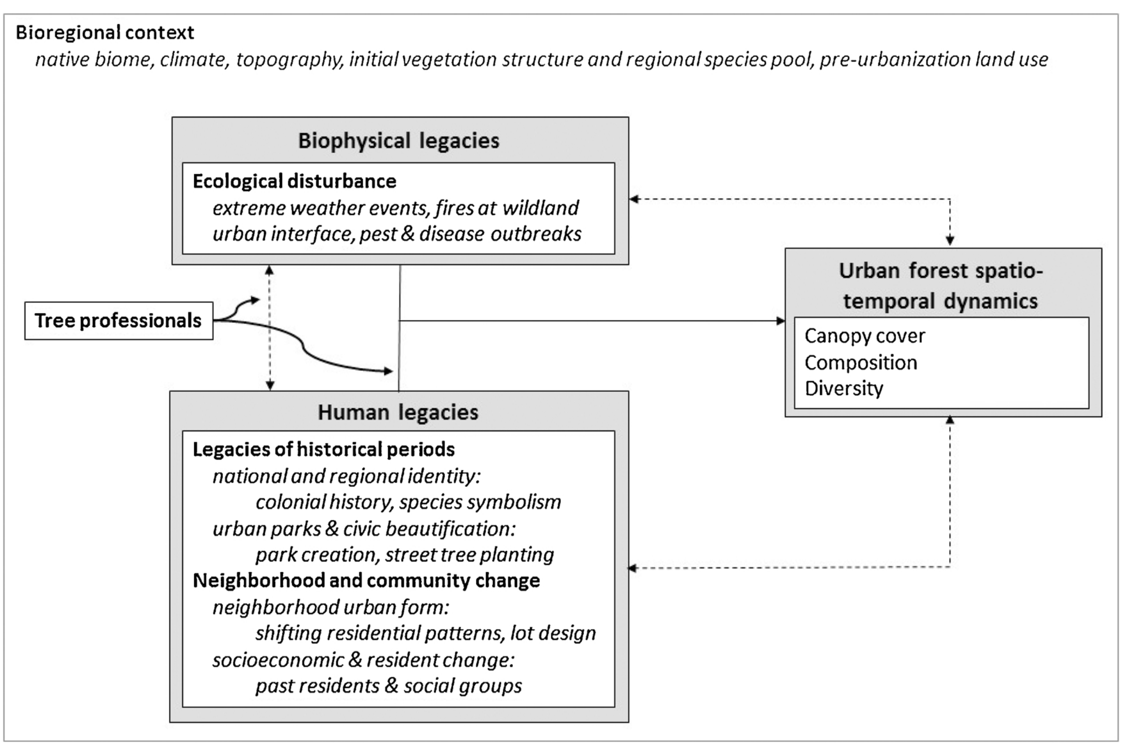

Fig. 1. Drivers of human and biophysical legacy effects in urban forests, which co-produce spatio-temporal dynamics of urban tree canopy cover, species composition, and diversity. The bioregional context represents the initial conditions in which a city grew and developed, and this context sets bounds on the impacts and trajectories of legacy phenomena. Solid straight lines represent interactive effects and dashed lines represent feedbacks. Solid curved lines indicate that urban tree professionals mediate the interactions and feedbacks between biophysical and human drivers.

ecological interactions (Cadenasso and Pickett, 2008; Vogt et al., 2015), with time as a central element (Pickett et al., 2016).

In this paper, we examine how legacy effects – the impacts that previous events, processes, and phenomena have on current properties or processes (Monger et al., 2015) – have shaped contemporary urban forests. Synthesizing existing literature, we discuss how urban forests developed their current patterns of tree canopy cover, species composition, and diversity, considering both inter- and intra-city variation. Urban tree canopy cover is the proportion of land covered by tree canopies as viewed from above (Raciti, 2006). Species diversity measures the number of species and distribution of their abundances (and is agnostic to species identity), whereas species composition refers to the identities of those species (Tilman and Lehman, 2002; Magurran, 2004). We focus on tree cover, composition, and diversity because they represent core elements of urban forest structure and spatial patterns. These elements vary across and within cities, and scholars have debated what kinds of urban forest patterns exist at varying spatial scales, and how these patterns were formed over time (Zipperer et al., 1997; Groffman et al., 2014; Yang et al., 2015; Jenerette et al., 2016; Gerrish and Watkins, 2018; Watkins and Gerrish, 2018). Additionally, evaluating and establishing appropriate tree cover levels and species mixes is central to sustainable urban forest management (Clark et al., 1997; Hauer and Peterson, 2016); that is, municipal foresters actively seek to alter these system characteristics.

To explore how urban forests developed their contemporary spatial patterns and structure – that is, how the urban forest came to be – we synthesize some of the major human and biophysical legacy effects that have shaped these systems. We incorporate interdisciplinary perspectives to provide a holistic understanding of how urban forests have changed through time to arrive at present system characteristics. We begin with an overview of the interconnectedness of structure, space, and time to stress how multiple disciplines recognize the value of historical perspectives and temporally focused analyses to understand landscape patterns. Next, we discuss the bioregional context for urban forest development, which represents the initial conditions in which a city grew and which continues to influence urban forest characteristics

Fig. 2. Abandoned or neglected urban properties showing (top row) vegetation regeneration in forested biomes (left: Philadelphia, Pennsylvania; right: Tampa, Florida) and (bottom row) in non-forested biomes (left: Sacramento, California; right: Riverside, California). Photos by D Traub, D Reilly, ML Cadenasso, and GD Jenerette.

today, setting bounds on how legacy effects play out. We then discuss how urban forest systems have been constructed through human drivers, with legacies from particular time periods as well as socioeconomic processes that cut across time periods. After this, we turn to biophysical drivers to discuss ecological disturbances, which have multi-faceted legacy effects on urban forests that are dependent on urban forest construction and management, as well as bioregional context. Finally, we discuss tree care professionals who mediate interactions and feedbacks across time between human and biophysical drivers. We have grouped drivers of legacy effects coarsely into biophysical and human categories (Fig. 1), but we discuss deeply entangled interactions throughout the paper. We then conclude with a call for interdisciplinary and mixed methods research to study legacy effects in urban forests. Our paper highlights examples from United States (US) and Canada, where much relevant urban forestry research has been conducted, and where the human and biophysical forces shaping urban forests – such as urban greening movements and disease outbreaks – have regularly crossed political borders.

2. Connecting structure, space, and time

In this paper, we emphasize that historical processes must be considered in any investigation that seeks to explain how urban forest structure and spatial patterns emerged within a given city, or across multiple cities. Indeed, theoretical frameworks in ecology and the social sciences recognize that the structure of a system is intimately linked to space and time. For instance, in rural forests ranging from New England to Amazonia, ecologists have increasingly recognized that current tree composition, spatial patterns, and ecosystem functions are explained by legacies of past human land use, including agriculture (Foster et al., 1998; Bürgi et al., 2017; Levis et al., 2017). Forest structure and patterns can therefore be best understood in light of history. Szabó (2010) noted that the fields of historical ecology and environmental history are built on the fundamental interconnectedness of history and ecology. Historical contingencies are also seen as a principal dimension of urban ecological complexity (Cadenasso et al., 2006).

Meanwhile, social scientists have also recognized the importance of temporal processes to spatial patterns. In human geography, Massey (1999) emphasized a unified understanding of space and time together, and "conceived of cities as open space-time intensities of social relations" (262). She urged a re-thinking of the meaning of space and history as a process of "the continuous creation of novelty," in contrast with oversimplifications of space as static (Massey, 1999, 274). Other geographers have written about spatio-temporal representation in geographic information systems (Couclelis, 1999) and measurement theories of time geography (Miller, 2005). In environmental sociology, Elliot and Frickel (2015) situated patterns of urban hazardous industrial sites in place through long-term iterative interactions between social and biophysical phenomena.

These conceptual and philosophical discussions about space-time from the social sciences share much in common with ecological discourse on why history matters (Szabó, 2010), as well as dynamic heterogeneity and historical contingencies in landscape patterns (Cadenasso et al., 2006; Pickett et al., 2016), in that all recognize human history and temporal processes as central pillars explaining space and place. Our examination of legacies in the urban forest context builds upon these multiple disciplinary traditions of understanding spatio-temporal dynamics. Indeed, while there have been numerous recent studies linking spatial patterns in urban forests to socioeconomic variation (e.g., the articles cited in the recent meta-analyses by Gerrish and Watkins, 2018; Watkins and Gerrish, 2018), there have been few studies examining the legacy effects of historical phenomena to link spatial patterns with temporal processes (but see Boone et al., 2010, Grove et al., 2014; Fahey and Casali, 2017; Grove et al., 2018).

3. Bioregional context

Bioregional context represents the initial ecosystem properties in which a city established and grew (Peters et al., 2011). The bioregional context of urban forests includes the surrounding biome, climate, topography, initial vegetation structure and regional species pool, and pre-urbanization land use. In addition to providing the starting condition for urban forests, this context impacts their development by constraining or enabling particular trajectories (ibid.).

Bioregional context influences how legacy effects have unfolded over time to produce current inter- and intra-city patterns, often interacting with human actions and processes. For example, the phenomenon of vegetation growth on abandoned or neglected lands in cities represents legacy effects following socioeconomic processes of population and economic decline. Yet whether those abandoned lands become emergent forests, or some other vegetation type, depends in part on bioregional context (Fig. 2). Cities located in forested biomes have seen forests reestablish on abandoned agricultural and estate lands, leading to scattered small wooded fragments in Syracuse, New York (Zipperer, 2002) and even a large park system in Philadelphia, Pennsylvania (Armstrong 2012; Milroy, 2016). In neighborhoods with declining populations, abandoned parcels can also become emergent forests. Vegetation composition and species richness on abandoned urban land differs considerably from pre-settlement habitat (Nassauer and Raskin, 2014). In Syracuse, emergent afforested patches have more total species and more non-native species compared to remnant patches (Zipperer, 2002). In contrast to cities that experience forest emergence on abandoned lands, vacant lands in cities situated in non-forested biomes with little precipitation would not be expected to increase in tree cover. In Sacramento, California, grasses and other low vegetation grow on vacant lots, and are then subsequently mowed to control fire risk (Kuang, 2015). In that city, planted trees rely upon irrigation, so vacancy or neglect can lead to young tree mortality (Roman et al., 2014).

Long-term change in a given city's total tree cover also relates to the biome in which the city resides. Zipperer et al. (1997) suggested that tree cover generally increases after the establishment of human settlements in ecoregions which lacked tree cover, but declines post-settlement in forested ecoregions. Consistent with that model, there were substantial increases in tree cover during urbanization in cities located in the shrub-dominated landscapes of coastal California (Nowak, 1993; Gillespie et al., 2012) and the mid-western prairie (Berland, 2012) while cities in the forested biomes of northeastern US were deforested during colonialization, and the tree cover was later gained back through conservation and afforestation (Stroud, 2015).

Present-day urban forest species composition at continental scales relates to climate factors. Urban forests in cold winter climates tend to be dominated by native species, while in warm climates, biodiversity is higher and dominated by imported species, especially species with showy flowers and fruits that reflect human preferences (Jenerette et al., 2016). This recently proposed climate tolerance and trait choice hypothesis explains urban forest compositional patterns across the US and Canada, counter to prior proposals of biome matching and urban homogenization (McKinney, 2006; Ramage et al., 2012). The climate tolerance component of Jenerette et al.'s (2016) analysis emphasizes that minimum winter temperature poses more of a constraint on urban tree species composition than does precipitation, because humans can irrigate in dry climates (yet precipitation continues to matter during periods of economic stress, see Ripplinger et al., 2017). The trait choice component of the hypothesis implies a sociocultural legacy of historical plant introductions, which we discuss further in the sections on human drivers and tree care professionals.

At the intra-city scale, bioregional context and fine-scale variation in environmental characteristics intersect with social processes. For instance, sections of South Lake Tahoe, California that are currently forested are drainage areas, presumably due to flood risk precluding residential development (McBride and Jacobs, 1986). In Cincinnati, Ohio, the hilly areas of the city have relatively high tree cover, which was explained by legacies of racial segregation that were tied to terrain and land use (Berland et al., 2015). Additionally, the imprint of pre-urbanization vegetation structure and composition can persist in modern tree cover, as demonstrated by research in Chicago, Illinois. That metropolitan region had a mix of prairie and woodland habitat before Euro-American settlement. In the contemporary landscape, areas that were historically *Quercus* (oak) woodlands continue to have high *Quercus* dominance as well as greater canopy cover and biomass than forests established in areas that were formerly prairies (Fahey et al., 2012; Fahey and Casali, 2017).

4. Human drivers

Urban forests are inextricably entwined with urban history. Here, we discuss sociopolitical phenomena have left prominent legacies on current tree cover, species composition, and diversity. Notably, the largest components of contemporary urban tree cover are generally parks, emergent patches, residential areas, and street trees (with considerable variation across cities in the proportions of those components, e.g., Zipperer et al., 1997, Zipperer, 2002; Grove et al., 2006; O'Neil-Dunne, 2011; Locke et al., 2017), so we pay particular attention to the human origins of these landscapes. In-depth historiographies of urban forests in the US have been carried out by others (Campanella, 2003; Lawrence, 2006; Jonnes, 2016), and our overview is far from exhaustive. Urban forest history across Canada has been less extensively studied, but we include Canadian literature whenever possible, and note linkages between legacies across the two countries. The first subsection below is centered on legacies of particular time periods, while the second subsection is about processes that cut across time periods.

4.1. Legacies of historical periods

4.1.1. Tree species connected to national and regional identity

The species composition of many urban forests is strongly influenced by the selection of species that held strong cultural or political meaning in the past. Certain species have been historically important to national and regional identity, often with roots back to the colonial era in North America. For British immigrants settling in New England and the mid-Atlantic colonies in the 1600s, trees became political symbols. In particular, *Ulmus americana* (American elm) held totemic significance. For example, a peacekeeping agreement between William Penn and the Lenni-Lenape tribe took place under a Treaty Elm in Philadelphia; this event has been memorialized in paintings and literature (Wertz and Callender, 1981). *U. americana* was also a potent symbol of political resistance leading to American independence (Schlesinger, 1952; Jonnes, 2016). This species later became an iconic element of US towns and by the 1930s some 25 million had been planted across the country (Rutkow, 2012). This widespread historical abundance of *U. americana* was a legacy of cultural and political symbolism. These populations were then decimated by *Ophiostoma* spp. (Dutch elm disease, DED; Jonnes 2016). However, *Ulmus* has not been entirely wiped out, which can be partially explained by its continued cultural appeal (Heybroek, 1993). Some cities have maintained small populations through aggressive treatments (Portland Parks and Recreation, 2017), while others have created new populations by planting tolerant hybrid varieties. For instance, recent *Ulmus* hybrid plantings in New Haven, Connecticut honored its "Elm City" nickname, a moniker that persisted even after the town's original *U. americana* population was lost (Campanella, 2003; MacMillan, 2014).

In the western US, Spanish colonial influence is seen in the history and enduring presence of palm trees. Spanish missionaries introduced exotic palms to California, with the first palm reportedly planted in 1769 in San Diego (Trent and Seymour, 2010). While palms are common today in southern California, only one species, *Washingtonia filifera* (California fan palm), is native to the area. Yet palms have become part of southern California identity, signifying "health, wealth, warmth, leisure, sophistication, glamour" (Farmer 2013, 337). Recent concerns about their disease potential and insufficient environmental benefits, as well as municipal responses to those issues, caused media controversy that Los Angeles was abandoning its palm-filled image, reinforcing the powerful symbolism of palms in the public's imagination of southern California (Farmer, 2013).

In Canada, the widespread planting of *Acer* spp. (maple) is a legacy of the history and symbolism of that genus in national identity. The maple leaf has been Canada's emblem since the 1700s. Starting in the 1800s, politicians and troops wore maple leaf badges to identify as Canadian, and the maple leaf first appeared on coins in 1876. Given their symbolism, *Acer* spp. were often planted during official ceremonies (Gordon and Osborn, 2004; McCue, 2002). The representation of the maple leaf as the symbol of Canada was solidified in 1965 with the adoption of the current flag (Fraser, 1994). As a legacy of the long association of maples with Canadian identity, many Canadian cities from the early 20th century to today have planted numerous maple species including *A. platanoides* (Norway maple), *A. rubrum* (red maple), *A. saccharinum* (silver maple), *A. saccharum* (sugar maple), and modern hybrids (Dean, 2011; Vander Vecht and Conway, 2015).

4.1.2. Urban parks movement and civic beautification

Although trees were planted in American and Canadian cities in the colonial era, extensive urban forest systems did not emerge until the mid-1800s (Dean, 2005, Lawrence, 2006). The creation of urban parks and civic beautification movements from the mid-1800s to early 1900s shaped the distribution and extent of urban tree cover, as well as the species palette of urban forests, producing legacy effects on current structure and spatial patterns. In the 19th century, the population explosion, pollution, and public health concerns associated with industrializing cities inspired reform-minded civic leaders and city elites to transform the physical fabric of cities, including new public parks, park systems, and parkways (Schuyler, 1986). This period also spawned what has been described as the first urban tree movement in the US (Jonnes, 2016). Predicated on miasma theory (which held that many diseases were caused by noxious air) and English landscape garden theories, public health and international transmission of ideas directly informed these green space innovations and associated tree planting activities (Lawrence, 2006; Eisenman, 2016).

Civic improvement and beautification were also prominent rationales for tree planting in this era. Arboreta, botanic gardens, and new types of civic and residential green spaces emerged in or near urban centers. Widespread tree planting in 19th century US cities expressed a distinctly American aspiration for an "urban pastoral" (Campanella 2003, 127). This patriotic spirit also undergirded the invention of Arbor Day in 1872 as a national holiday (Cohen, 2004). The Arbor Day Foundation contributed to tree planting in bioregions that are not naturally forested, especially the mid-western plains (Jonnes, 2016). By the early 1900s, most American cities were characterized by "an immense arboreal landscape" (Lawrence, 2006, 247). Women played central roles as social activists and landscape professionals during this era, spurring tree planting in public spaces (Dümpelmann, 2005). Examples include horticulturalist Katherine Sessions as the "Mother of Balboa Park" in San Diego (MacPhail, 1976, 4), geographer Eliza Scidmore promoting Japanese *Prunus* (cherry) plantings in Washington, DC (Jonnes, 2016), and Ellen Harrison as an advocate, fundraiser and supervisor of tree planting on a college campus in Philadelphia (Roman et al., 2017). Indeed, women's civic improvement societies – which featured tree planting as a prominent aspect of their work – have been credited with "[saving] the American city between the Civil War and World War I" (Spain, 2001, 2).

While Canadian urban tree planting during this era has not been as extensively studied, literature on the topic points to rationales for park creation and civic beautification similar to US cities, and often with direct references to US practices. The eminent American landscape architect Frederick Law Olmsted, Sr. – who designed Central Park in New York, New York among many other parks – later designed Mount Royal Park in Montréal, Quebec (Murray, 1967). Olmsted's so-called "disciples" designed many more urban parks in Canada (Pollock-Ellwand, 2006). Meanwhile, street trees were extensively planted by private residents in the late 1800s for shade and ornamental values in Ottawa, Ontario, with politicians seeking to emulate the tree-lined streets in US cities (Dean, 2005). Indeed, urban planning trends – including park design and planting movements – have long exhibited diffusion across international borders, as evidenced by Vancouver, British Columbia adopting park design proposals from both American and British planners (Ward, 1999). By the end of the 19th century, the ubiquitous presence of trees in North American cities contributed to an urban planning and design norm described by Lawrence (2006, 221) as "a model for the world."

The legacies of these internationally connected social movements are critical to understanding contemporary urban forest spatial patterns and structure. For example, in some cities, urban park systems now constitute a substantial portion of existing tree canopy and can therefore have a significant impact on the species composition of the urban forest as a whole. In San Francisco, California, the Australian *Eucalyptus globulus* (blue gum) is the most common tree in the city, accounting for 15.9% of the total urban forest (Nowak et al., 2007). The prevalence of *E. globulus* today is explained by widespread plantings of that species in parks of the San Francisco Bay Area after the 19th century Gold Rush, when the city's population exploded and Golden Gate Park was converted from sand dunes to an "Australian-made park" (as quoted in Farmer, 2013, 163). The high tree cover in Bay Area parks today, and the abundance of *E. globulus* in those parks, represent legacy effects of foresters, nurseries, and marketers from the second half of the 1800s through the early 1900s, who encouraged *Eucalyptus* plantings to beautify treeless landscapes, protect watersheds, and provide forest resources lost from the cutting of native *Sequoia sempervirens* (coast redwood) and *Quercus* (Farmer, 2013; Simon, 2014).

Similarly, current street tree composition reflects legacies of civic improvements from this period. For example, by 1939, Philadelphia had planted an estimated 153,000 *Platanus* × *acerifolia* (London plane; Walter, 1946) and in the 1960s this tree constituted an estimated one-third of street trees in the city (Li, 1963). Despite challenges with *Ceratocystis platani* (canker stain) which caused some removals in the mid-1900s (Walter 1946), today, *P. acerifolia* is still one of the most common street trees in Philadelphia, and one of the largest trees present (DVRPC, 2013; Nowak et al., 2016). Its prevalence is a legacy of plantings from the civic beautification movements of the late 19th and early 20th centuries, when Philadelphia's boulevards and neighborhood streets were lined with *P. acerifolia*. This includes the monumental Benjamin Franklin Parkway, modeled after the Champs-Elysées in Paris, France, which itself was also lined with *P. acerifolia*. (Brownlee, 1989; Forrest and Konijnendijk, 2005). Indeed, *P. acerifolia* is considered "the most widely planted of all city trees" (Lawrence, 2006, 273), and has long been appreciated for its large size, rapid growth, and tolerance to urban environmental stresses (Pack, 1922; Dirr, 2011). The popularity of this tree has been attributed to the English origins of the urban parks

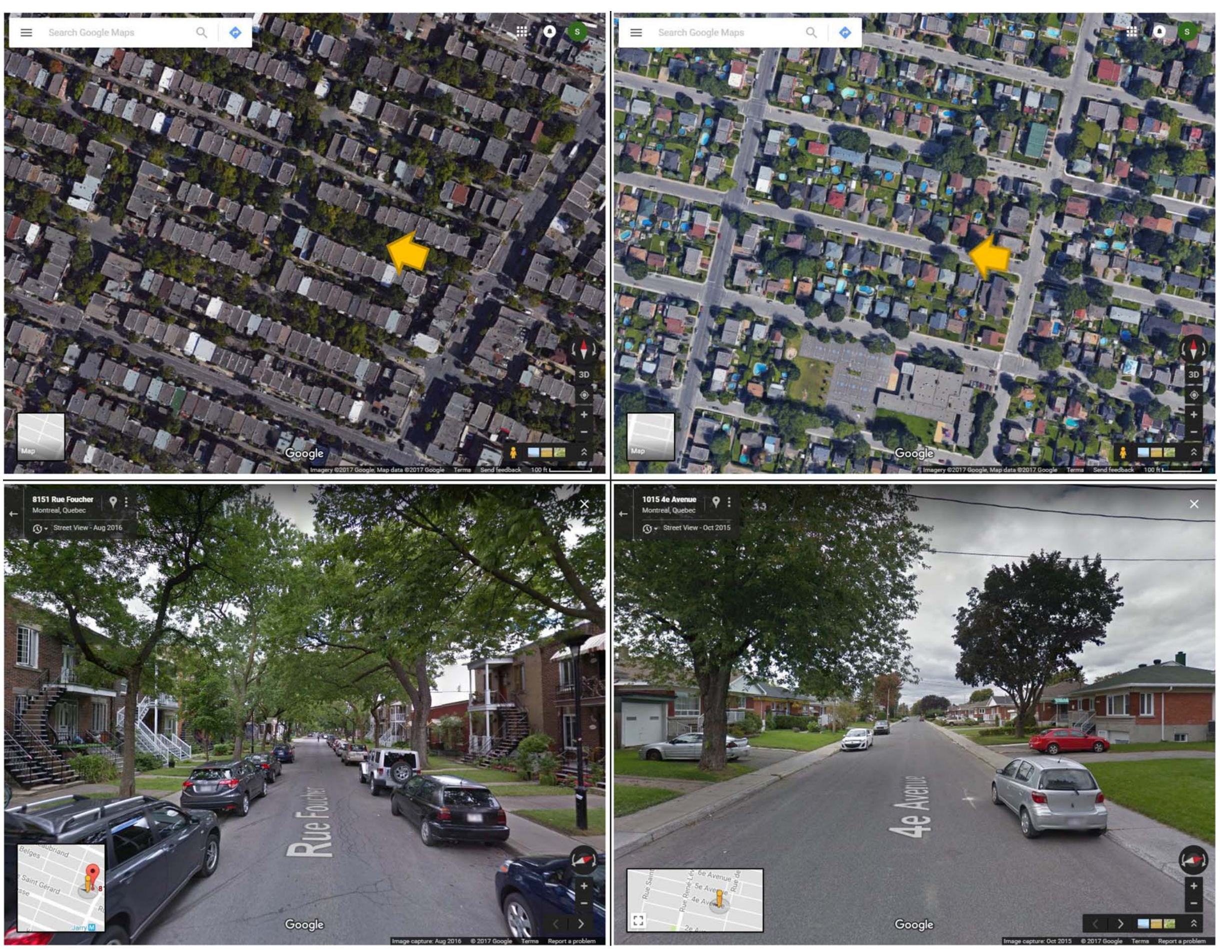

Fig. 3. Tree cover in neighborhoods with contrasting urban forms in Montréal, Quebec. Older multi-family residential street with abundant street trees in the Villeray-Saint-Michel-Parc-Extension borough (left), and newer single-family residential street with fewer street trees in the Rivière-des-Prairies-Pointe-aux-Trembles borough (right). Median year of residential buildings in each borough was 1949 and 1977, respectively (Pham et al., 2013). Images courtesy of Google Maps and Google Street View. Arrow indicates location and direction of Street View image.

movement: “When the English style of landscape garden spread… the hybrid plane went with it” (Lawrence, 2006, 216). The presence of *P. acerifolia* today as a dominant canopy tree along streets in many cities is a legacy of its sociocultural significance in the civic beautification era combined with historical local planting decisions by tree professionals.

4.2. Legacies of neighborhood and community change

4.2.1. Neighborhood urban form

Neighborhood urban form leaves a legacy that impacts where public and private trees can grow, which in turn affects tree canopy distribution and diversity. Urban form describes the physical conditions and built environment of a city, such as the geographic patterns of land uses and their densities, as well as the spatial design of transportation infrastructure (Anderson et al., 1996). While the urban parks movement created green spaces that shaped urban form at the municipal scale (Schuyler, 1986), this section focuses on urban form at the neighborhood scale, especially residential development styles.

Neighborhood design in the US fundamentally changed in the mid-1900s, precipitated by mass-production of automobiles and single-family homes, federal support of highway building, and white migration from urban centers, which was associated with racial prejudice and supported by federal, state, and local laws (Rothstein, 2017). Urban settlements decentralized and sprawling suburban landscapes emerged (Anderson et al., 1996). By 1970, more Americans lived in suburbs than central cities or rural areas (Hayden, 2003). Suburban areas likewise expanded drastically in Canada during the mid-20th century, spurred by housing policies, sometimes with racial undertones (Harris, 2004). The proliferation of single-family houses that dominated post-WWII altered the private land area available for tree planting. Larger lot sizes (Conway, 2009) and larger building set-backs (Pham et al., 2017) have been positively associated with vegetation cover. In both the US and Canada, urban areas with a higher proportion of single-family residential properties often have greater tree cover (Troy et al., 2007; Conway, 2009, Pham et al., 2017). Areas with more residential lands can also have high overall tree species diversity (Bourne and Conway, 2014), potentially related to homeowner choice in species selection. In residential neighborhoods, the proportion of trees situated along streets or in yards can relate to housing style. In Montréal, Quebec, older high-density areas with less plantable space on private lots have an urban forest dominated by street trees (Pham et al., 2013, Fig. 3). This geographical arrangement of trees along streets or in private yards represents a legacy of shifting urban form.

In analyses that combine urban tree cover with contemporary socioeconomic data (e.g., US Census records), when building age is incorporated, it is consistently found to be correlated with tree cover, which hints at temporal explanations of tree cover variation. Troy et al. (2007) detected a parabolic relationship between building age and the presence of vegetation in Baltimore, Maryland, where the positive association reaches a maximum cover at 40–50 years and then decreases; other studies have since corroborated those findings (Landry and Chakraborty, 2009; Locke et al., 2016; Pham et al., 2017). This relationship may reflect the normal life cycle of planted trees: growth followed by decline and removal (Roman et al., 2016). Alternatively, building age may capture differences in urban form or development patterns. When controlling for age of development, Lowry et al. (2012) found that higher street density and connectivity in Salt Lake County, Utah were associated with greater tree canopy only in the short term (15 years), whereas the association between tree canopy and lot size became positive only in the long term (after 95 years). Also in Salt Lake County, older neighborhoods had higher numbers of trees and higher species richness, but with variation in effects for street and yard trees, and across income levels (Avolio et al. *in press*). That study also suggested a relatively short-lived fad in preference for *Pyrus calleryana* (Callery pear) as a street tree, leading to its dominance in some neighborhoods that may shift over time as this species has since gone out of favor. Neighborhood urban form and the policies that shape it are thus important drivers of urban forest spatio-temporal dynamics, including patterns of private versus public tree ownership, decadal-scale fluxes in tree cover, and the impact of species preferences from different periods of neighborhood development.

4.2.2. Socioeconomic change and resident legacies

Urban forest cover, species composition, and diversity are also interrelated with sociodemographic legacies at household and neighborhood scales. Yet connections between socioeconomic change and current urban forest characteristics are not necessarily consistent across cities. Environmental justice explanations typically associate canopy cover with higher socioeconomic status (Heynen and Lindsay, 2003; Schwarz et al., 2015). Consistent with that pattern, vegetation cover and income were positively associated over time between 1970 and 2000 in Phoenix, Arizona, suggesting a gradual concentration of vegetation into higher income neighborhoods (Jenerette et al., 2011). However, in Baltimore, the black population currently lives in close proximity to parks, contrary to relationships between tree cover and race in other cities; this pattern reflects legacies of formal and informal segregation that restricted where blacks could live (Grove et al., 2018). Other research in Baltimore points to the importance of temporal lags in urban forest spatial patterns. Contemporary vegetation cover and structure in that city can be understood in terms of neighborhood characteristics, social groups, and urban renewal planting programs in the 1950s–60 s (Merse et al., 2009, Boone et al., 2010). This reveals that local sociopolitical history helps to explain municipal-scale urban forest patterns, particularly idiosyncrasies that run counter to broad trends.

At even finer spatial scales, household-level changes and resident behaviors influence property-level tree characteristics to create legacy effects. Summit and McPherson (1998) found that homeowners are most likely to plant trees in their first five years of residency, thus decisions during this initial period potentially have a decades-long influence on yard tree canopy and species composition. Additionally, residents' landscaping behavior can be influenced by neighborhood norms, length of residency in a metropolitan region, and nursery offerings (Nassauer et al., 2009, Larson et al., 2017). Household demographics and preferences also relate to tree traits which can influence canopy cover and species composition (Avolio et al., 2015b; Avolio et al. *in press*). Homeowner turn-over and residential yard management are therefore interconnected with the legacies of socioeconomic shifts discussed above.

5. Biophysical drivers: ecological disturbance

In this section, we focus on extreme weather events, fire, and pest and disease outbreaks, which are relatively discrete events, referred to as pulse disturbances. The legacy effects of ecological disturbance events are multi-faceted, including direct canopy loss from the event itself, indirect loss through pre-emptive removals due to concerns of risk and vulnerability, and shifts in management approaches regarding tree planting and species selection. The varying trajectories of disturbance legacies across and within cities are also influenced by how humans constructed the urban forests and bioregional context. While ecological disturbances are by no means the only biophysical drivers of legacy effects, they are the most well-studied in the urban forestry literature.

Extreme weather events (e.g., wind, ice/snow, flooding, and drought) can have intense and lasting effects on urban forests (Duryea et al., 2007). The effects of extreme weather on canopy cover can be widespread (e.g., hurricanes and regional ice storms) or localized (e.g., tornadoes and flooding). Certain species and larger individuals tend to be more susceptible to damage from wind and ice, which can decrease the abundance of large-canopied trees in urban areas (Hauer et al., 2006). Impacts can also vary greatly across the landscape in relation to factors such as slope position, proximity to floodplains, and built environment features such as urban canyons between large buildings (Lopes et al., 2009). There is also regional variation among cities in the frequency of extreme weather and the potential for such events to have lasting impacts on canopy cover. For example, the hurricane-prone region of South Florida experiences frequent wind disturbances, but also has a species pool purposefully planted to be resistant to high winds (Duryea et al., 2007), which could moderate the legacy effects of storms. Extreme weather events can also influence residential property management, such as decisions to remove large healthy trees following an ice storm in Toronto, Ontario (Conway and Yip, 2016), as well as long-term policy changes attempting to reduce risk for future events (Brzozowski, 2004; Kochanoff, 2004). Storm-related tree losses have led arborists in many cities to emphasize small-stature trees under utility lines to avoid problems from large shade trees becoming hazardous over time (Miller et al., 2015). This species shift is a legacy effect of storms in the form of altered management.

Fire impacts urban forests at the wildland-urban interface in the western regions of the US and Canada. For example, historical plantings of *E. globulus* and *Pinus radiata* (Monterey pine) to protect watersheds in Berkeley and Oakland, California transformed suburban hillsides previously composed of native fire-adapted *Quercus* woodlands. The new species composition, combined with building materials and residential development patterns, increased fire risk (Simon, 2014). The fire legacies in this system include direct canopy loss as well as removal of fire-susceptible species, although such removals can be contentious; fire-susceptible *E. globulus* stands may remain due to public affinity for this introduced species (Nowak, 1993; Farmer, 2013).

Finally, pests and pathogens have an outsized and long-lasting influence on urban forest change through time. Pest and disease outbreaks illustrate how interactions and feedbacks between biophysical and human drivers co-produce legacy effects. As previously discussed, streets were often historically lined with monocultures (Richards, 1983; Campanella, 2003; Lawrence, 2006; Jonnes, 2016). This planting strategy favored *U. americana* in the northeastern and mid-western US and southeastern Canada, making cities susceptible to devastation caused by DED during the mid-20th century, when many cities lost substantial canopy (Jonnes, 2016). For example, in Milwaukee, Wisconsin, tree cover along streets was reduced by half between 1963 and 1979, with street tree cover finally recovering to pre-DED levels after forty years (Plan-It Geo, 2015, Fig. 4). In another example, Syracuse lost nearly half of its street Trees – and almost all of its *U. Americana* – between 1951 and 1978 (Richards and Stevens, 1979).

In response to the DED outbreak, tree professionals called for urban tree species diversification as a way to reduce vulnerability to pests and disease (Raupp et al., 2006). Since the 1970s, several diversity management guidelines have been suggested, typically limiting the proportion of trees from the same taxonomic groups, with more recent systems proposing to manage vulnerabilities in the context of multi-host pests and diseases (Laçan and McBride, 2008). Implementing diversification strategies has remained challenging due to limited nursery stock (Sydnor et al., 2010), little understanding of diversity benefits by nursery growers (Conway and Vander Vecht, 2015), and the tendency to rely on few urban-tolerant species (Cowett and Bassuk, 2017). Furthermore, lining streets with a single tree species is still occasionally recommended for aesthetics, even though spatial clustering can facilitate pest spread (Greene and Millward, 2016). In the US, many mid-Atlantic street tree populations remain dominated by a few species (Cowett and Bassuk, 2017). However, some municipal foresters are planting a more diverse species palette (Vander Vecht and Conway, 2015), which could be expected to produce legacy effects on composition and diversity in years to come.

Different response strategies to DED have also resulted in divergent rates of canopy loss, with aggressive treatment slowing the rate of tree removal. For instance, the rapid and drastic decline in street tree canopy cover in Milwaukee was due to a policy of tree pre-emptive removal, prior to the development of DED treatments. However, if managers had been able to use treatments that are available today, an estimated one-third of the city's original *U. americana* population would still be alive (Plan-It Geo, 2015). Indeed, when DED later hit the northwestern states in the 1980s, Portland, Oregon began a regular monitoring and treatment program, with only a few dozen trees removed each year (Portland Parks and Recreation, 2017). Lessons

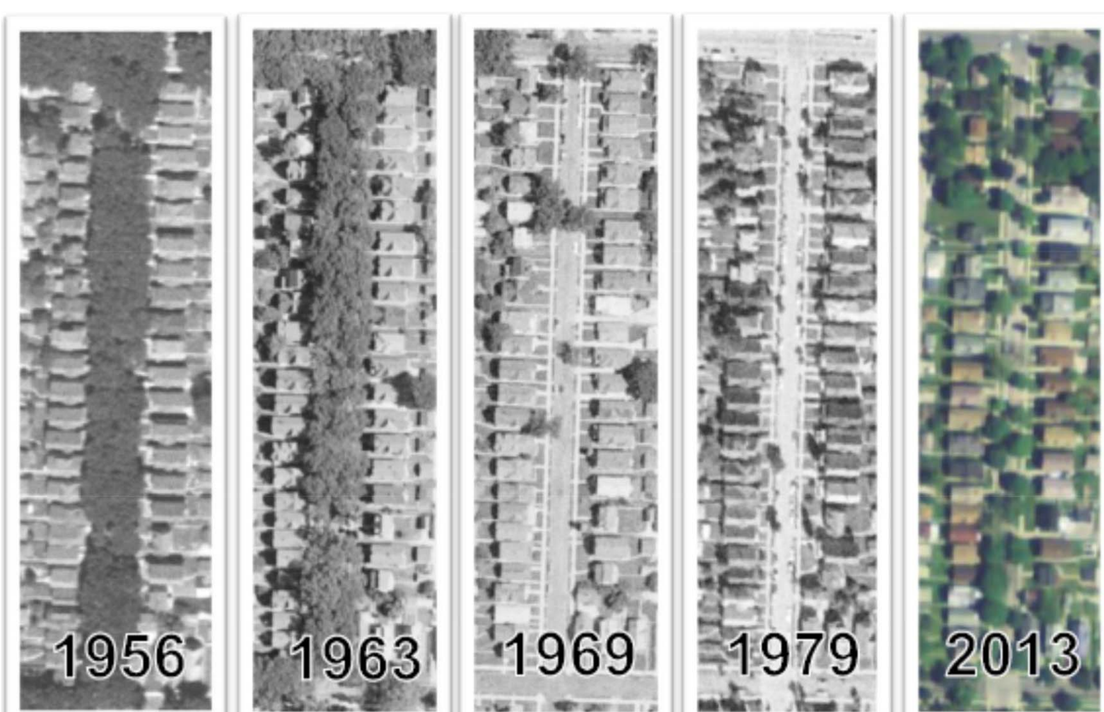

Fig. 4. *U. americana* street tree canopy cover loss in Milwaukee, Wisconsin, showing rapid decline from DED in the 1960s, with later canopy gains from new plantings (Plan-It Geo 2015). Images courtesy of Plan-It Geo.

learned from DED create their own legacy effects that influence management responses to new pest and disease threats (Poland and McCullough, 2006; Berland and Elliott, 2014). With the recent emergence of *Agrilus planipennis* (emerald ash borer; EAB), and treatments already available, municipalities might carry out steady treatments over many years, or alternatively, rapid pre-emptive removals (McCullough and Mercader, 2012; Hauer and Peterson, 2017). Different management responses to pest and disease outbreaks like DED and EAB can therefore contribute to variation in legacy effects based on the decisions of local policy-makers and tree professionals, in conjunction with the timing of available treatments.

6. Urban tree professionals

Arborists, urban foresters, horticulturalists, and tree nurseries are central players in urban forest systems, both currently and historically; their fingerprints are seen in all of the other themes in this paper. We treat tree professionals separately from the other human drivers because these professionals play a crucial role in mediating interactions and feedbacks (Fig. 1). The direct function of tree professionals in shaping the urban forest through species selection, overseeing planting and maintenance, responding to disturbance, removing trees, and communicating with policymakers and residents is often under-appreciated (Bardekjian, 2016a, Bardekjian, 2016b).

Horticulturalists and the nursery industry have been major drivers of urban forest composition, as they introduced a wide variety of exotic trees into urban landscapes, directly impacting composition and diversity. *Ginkgo biloba*, for example, was planted in the private collection of wealthy horticulturalist William Hamilton in Philadelphia in the mid-1700s and eventually made widely available by a nursery (Li, 1963, Jonnes, 2016). Throughout the 18th and 19th centuries, wealthy private individuals and families maintained extensive plant collections, often seeking novel exotic species (McPherson and Luttinger, 1998). The tree nursery industry has directly influenced the quality, quantity, and types of trees available for planting in cities. Nursery catalogs in Los Angeles showed a five-fold increase in the number of species available from the early 1900s to the early 2000s (Pincetl et al., 2013). This dramatic increase in species availability was largely attributed to increases in exotic species, and can help explain past and current urban tree diversity patterns.

The professionalized labor force engaging in a field of practice centered on the planting, maintenance and removal of trees emerged in the late 19th century. In the 1890s, the legislatures of several New England states passed the first "Tree Warden Laws," which empowered municipalities to appoint tree wardens in charge of tree care. A new professional emerged, "variously called urban forester, city forester, or municipal arborist" (Ricard 2005, 231). These staff were responsible for overseeing trees in public parks, plazas, and along streets. By the end of the 19th century, street trees were a legitimate area of municipal responsibility (Campanella, 2003) in cities ranging from New York to Ottawa (Gerhold, 2007; Dean, 2005). Such municipal activities dovetailed with the expansion of tree care companies (Jonnes, 2016). These municipal and contracted professionals were integral to designing and managing new green spaces that emerged through the previously discussed city parks and civic beautification movements.

When selecting species to plant, in addition to previously discussed cultural considerations and nursery availability, municipal arborists also weighed biological characteristics of trees, such as rapid growth and tolerance of urban environmental stresses (e.g., air pollution, challenging street tree sites); such characteristics were key to the historical popularity of *P. acerifolia* and *U. americana* (Richards, 1983; Lawrence, 2006). Furthermore, the legacies of historical species selection decisions by tree professionals are seen in present-day urban forest composition, such as the previously discussed prevalence of *E. globulus* in San Francisco and *P. acerifolia* in Philadelphia. These tree professionals in individual cities were embedded within domestic and international networks, exchanging information about what and where to plant, and spreading planting material through the nursery trade (Oberle, 1997; Farmer, 2013). For instance, in Philadelphia in the late 1800s and early 1900s, horticulturalist and nursery owner Thomas Meehan and his sons were influential across the US and internationally through gardening publications and tree sales (Oberle, 1997); the Meehan publications included extensive discussion about tree species characteristics and suitability for planting in various urban locations (Chandler, 1911).

By the early 20th century, the professionalization of urban tree care was well underway. In 1924, the first professional society of arborists and urban foresters, the National Shade Tree Conference, was established in the US (Campana and ISA Staff, 1999). The organization later broadened its scope beyond the US, and has been known since 1976 as the International Society of Arboriculture (ISA). In the 1960s-70s, urban forestry became a more widely-studied academic discipline and subject of scientific research. A key figure from this era was Erik Jorgensen, "Canada's first urban forester," who promoted urban forestry as a distinct field of study (Kenney, 2011). In fact, the development of his urban forest pathology and arboriculture program at the University of Toronto was motivated by the DED crisis (Dean, 2008), meaning that the expansion of the field of urban forestry is a legacy of ecological disturbance. Along with the growth of ISA came the development of best management practices on topics such as pruning (Gilman and Lilly, 2008), tree inventories (Bond, 2013), planting (Watson, 2014), and pest management (Wiseman and Raupp, 2016). These best management practices influence strategies from municipalities, nonprofits, and consulting arborists concerning where to plant, what to plant, how to preserve trees, and when to remove them. Indeed, local arborists are "the frontline workers in urban forestry" (Bardekjian, 2016a, 255) and they influence urban forest management through various rules and policies (Mincey et al., 2013) as well as by understanding and negotiating agency in multiple ways (Bardekjian, 2016b).

The tree professionals discussed above have varying geographic spheres of influence, from municipal arborists to national tree care companies to internationally networked horticulturalists and foresters, and their work can intersect with technological shifts, from pruning tools to remote sensing (O'Neil-Dunne et al., 2014; Johnston, 2015). Assessments of legacy effects ranging from ecological disturbances to tree planting movements should explicitly incorporate the decision-making roles of tree care professionals, and their grounding in institutions and technologies from different eras.

7. Conclusions

The continuously changing character of cities creates layers of legacies on the landscape, altering urban forests through complex interactive processes over time (Fig. 1). In our synthesis of literature pertaining to legacy effects in urban forest systems, we found the following:

1. *Bioregional context sets bounds on the impacts and trajectories of legacy phenomena*, as evidenced by the continuing importance of minimum temperature on urban species composition at continental scales, and the varying types of vegetation that can emerge on vacant lands in different biomes.
2. *Urban trees are part of an inherited landscape*, reflecting legacies of past greening movements, cultural and political symbolism of certain species, changing socioeconomic conditions and neighborhood form, and resident behaviors.
3. While there are common threads in legacy effects across many cities for similar historical time periods, neighborhood forms, and bioregional contexts, there can be idiosyncrasies in urban forest patterns and trajectories between different cities. It is important to recognize *the crucial role of local sociopolitical history*.
4. The human and biophysical drivers that shape urban forests over

time are intimately connected through interactive effects and feedback loops, with *tree care professionals* often involved in these connections. We found strong evidence that the short-and long-term impacts of ecological disturbance events were mediated by these professionals.

We contend that historical events and processes, and their associated legacies and time-lagged interactions, have too often been overlooked in analyses of urban forest spatial patterns. Historical perspectives are imperative to improve understandings of contemporary urban forest characteristics and the underlying mechanisms that produced those characteristics (Ramalho and Hobbs, 2012). Although historical narratives of urban forest development have been published for a few cities (e.g., McPherson and Luttinger, 1998; Milroy, 2016), historical investigations are rarely used to explain contemporary urban forest characteristics (but see Fahey et al., 2012; Grove et al., 2018; Roman et al., 2017). Meanwhile, other studies have documented the extent of urban tree cover change over many decades (e.g., Berland, 2012; Gillespie et al., 2012), without historical research to explain how that change occurred.

Urban forestry as a field of *practice* is inherently interdisciplinary (Vogt et al., 2016). However, there is a need for more interdisciplinary *research* to understand how the urban forests of various cities developed their current characteristics, drawing upon expertise of historians, urban geographers, sociologists, anthropologists, landscape architects, urban planners, and ecologists. New interdisciplinary investigations should combine qualitative and quantitative analytical approaches to unpack human and biophysical legacy effects, and their impact on urban forest structure, spatial patterns and temporal trends. Such mixed methods studies could reveal processes which have created current urban forest properties at intra- and inter-city scales, uncover social and biophysical drivers that may cross political borders, and illuminate how and why convergent and divergent trajectories have arisen. Moreover, urban forests present a tremendous opportunity to study legacy effects given the archival records available about past policies, actors, planting trends, and disturbance events to uncover mechanisms of change over time, plus historical aerial photography and vegetation surveys to characterize that change (Dawson and Khawaja, 1985; Fahey et al., 2012; Gillespie et al., 2012; Pincetl et al., 2013; Simon, 2014; Fahey and Casali, 2017; Grove et al., 2018; Roman et al., 2017; Ogden et al. in press). In drawing connections between historical phenomena and legacy effects, our review drew heavily from investigations of species trends and regions that have been well-studied by historians – such as *U. americana* in the eastern US and Canada – but there are other historically important species and processes, even within this same region, that have not been as well-explored. For legacies pertaining to species composition, future research in this region could include introduced *A. platanoides* planted as a shade tree and subsequently invading nearby forests (Nowak and Rowntree, 1990; Zipperer, 2002), and the widespread popularity of *P. acerifolia* (Li, 1963; Lawrence, 2006). New legacies research could also extend to urban forests in other countries and continents, where different historical, cultural, political, socioeconomic, and biophysical forces may be at work (McBride, 2017), and where cities are much older than in the US and Canada.

Improving our understanding of the impacts of past events and processes can also aid in constructing potential scenarios for legacies that will arise from ongoing and recent phenomena. Such phenomena include, but are not limited to, the widespread adoption of million-tree planting campaigns, technologically-enabled tree cover assessments and goals, the influence of national institutions and expansion of local stewardship organizations, economic recessions, new pest and disease outbreaks, and climate change (Grove et al., 2006; Poland and McCullough, 2006; McKenney et al., 2007; Young, 2011, Fisher et al., 2012; Mincey et al., 2013; Hauer and Peterson, 2017; Jonnes, 2016, Ripplinger et al., 2017). These human and biophysical drivers are likely already altering canopy cover, species composition, and diversity, but their legacy effects on urban forest systems have not yet been well-documented. Historical analysis can help us imagine how various future scenarios might play out, based on the pace and process of prior change. By looking to the past to understand today's urban forest, we can better construct its future.

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