Ecological homogenization of urban USA

Peter M Groffman[1*], Jeannine Cavender-Bares[2], Neil D Bettez[1], J Morgan Grove[3], Sharon J Hall[4], James B Heffernan[5], Sarah E Hobbie[2], Kelli L Larson[6], Jennifer L Morse[1], Christopher Neill[7], Kristen Nelson[8], Jarlath O'Neil-Dunne[9], Laura Ogden[10], Diane E Pataki[11], Colin Polsky[12], Rinku Roy Chowdhury[13], and Meredith K Steele[5]

A visually apparent but scientifically untested outcome of land-use change is homogenization across urban areas, where neighborhoods in different parts of the country have similar patterns of roads, residential lots, commercial areas, and aquatic features. We hypothesize that this homogenization extends to ecological structure and also to ecosystem functions such as carbon dynamics and microclimate, with continental-scale implications. Further, we suggest that understanding urban homogenization will provide the basis for understanding the impacts of urban land-use change from local to continental scales. Here, we show how multi-scale, multidisciplinary datasets from six metropolitan areas that cover the major climatic regions of the US (Phoenix, AZ; Miami, FL; Baltimore, MD; Boston, MA; Minneapolis–St Paul, MN; and Los Angeles, CA) can be used to determine how household and neighborhood characteristics correlate with land-management practices, land-cover composition, and landscape structure and ecosystem functions at local, regional, and continental scales.

Front Ecol Environ 2014; 12(1): 74–81, doi:10.1890/120374

Urban land-use change has been identified as one of the major components of environmental change because of its effects on climate, water, biodiversity, carbon (C), and nutrients across large areas of the globe (Foley *et al.* 2005; Grimm *et al.* 2008). Between 1982 and 1997 the amount of urbanized land in the US increased by almost 50%, extending over 1.4 million km^2 and encompassing more than 80% of the US population (Brown *et al.* 2005). Most of this growth was suburban and exurban. According to results from the US Census Bureau's national census in 2000 (www.census.gov/main/www/cen2000.html), suburban growth surpassed growth in cities, regardless of city-specific population dynamics and economic trajectories (Katz *et al.* 2003).

A visually apparent but scientifically untested outcome of contemporary US land-use change is ecological homogenization across urban areas, wherein human dominance and land-management practices render suburban systems more similar to other, geographically distinct cities than to adjacent native ecosystems (McKinney 2006; Pouyat *et al.* 2007; Pickett *et al.* 2011). Such homogenization would be exhibited in biophysical structure, where neighborhoods across biophysically different regions come to have similar patterns of human infrastructure (including roads, residential lots, commercial areas), vegetation structure, and aquatic features. This homogenization may also result in ecological transformation, with replacement of natural vegetation assemblages by turfgrass, popular or weedy plant species, and impervious surfaces.

Residential land management is fundamentally a local process, an expression of the decisions of individual land managers and households. However, decisions on yardscaping and other kinds of management may be tied not only to variables at the scale of individuals or households, but also to broader social structures (eg family dynamics), socioeconomic status (eg wealth), neighborhood-level norms, and national-scale marketing and retail activity (Grove *et al.* 2006; Zhou *et al.* 2009; Larson *et al.* 2010; Roy Chowdhury *et al.* 2011; Cook *et al.* 2012). Most fundamentally, cities are socioecological systems that are built by and for humans. There is a strong need to develop a theory and science of human habitats comparable to the study of the habitats of other species.

We hypothesize that the multi-scalar drivers and dynamics of residential land management lead to two important continental-scale patterns in urban ecosystem structure and function. First, similarity in people's decision-making processes across broad areas promotes convergence and homogenization in urban ecosystem structure and function across biophysically dissimilar settings. Thus, residential ecosystems in different places are more

In a nutshell:

- Urban land-use change may be homogenizing the US, producing residential ecosystems/landscapes that are more similar to each other than to the natural ecosystems that they replace
- This homogenization may have continental-scale effects on carbon sequestration, microclimate, and other ecosystem properties
- Urban homogenization may be driven by a specific set of human actions that are manifest at the household parcel scale and vary along definable and scalable geodemographic axes

[1]*Cary Institute of Ecosystem Studies, Millbrook, NY* [*]*(groffmanp@caryinstitute.org);* [2]*Department of Ecology, Evolution, and Behavior, University of Minnesota, St Paul, MN;* [3]*Baltimore Field Station, USDA Forest Service, Baltimore, MD;* [4]*School of Life Sciences, Arizona State University, Tempe, AZ;* *continued on p 81*

similar to each other than they are to the native ecosystems that they replaced; for instance, a Phoenix residential lawn is more ecologically similar to a Baltimore yard than to Sonoran Desert ecosystems (Figure 1). Second, because residential management is driven mainly by household composition and socioeconomic characteristics, as well as by neighborhood-level norms, we hypothesize that neighborhoods with similar demographic and lifestyle characteristics (eg age, socioeconomic status, life stage, ethnicity) and social preferences (eg values and interests) across different cities will have more similar landscaping preferences and practices than different neighborhoods within the same city. More generally, homogenization is driven by human habitat preferences, as expressed through socioeconomic factors and lifestyles. The hypothesized result is that demographically similar neighborhoods in Phoenix and Baltimore have more similar ecosystem structure and function (eg the distribution of grass, trees, and shrubs) than demographically dissimilar neighborhoods within each metropolitan area (Figure 2).

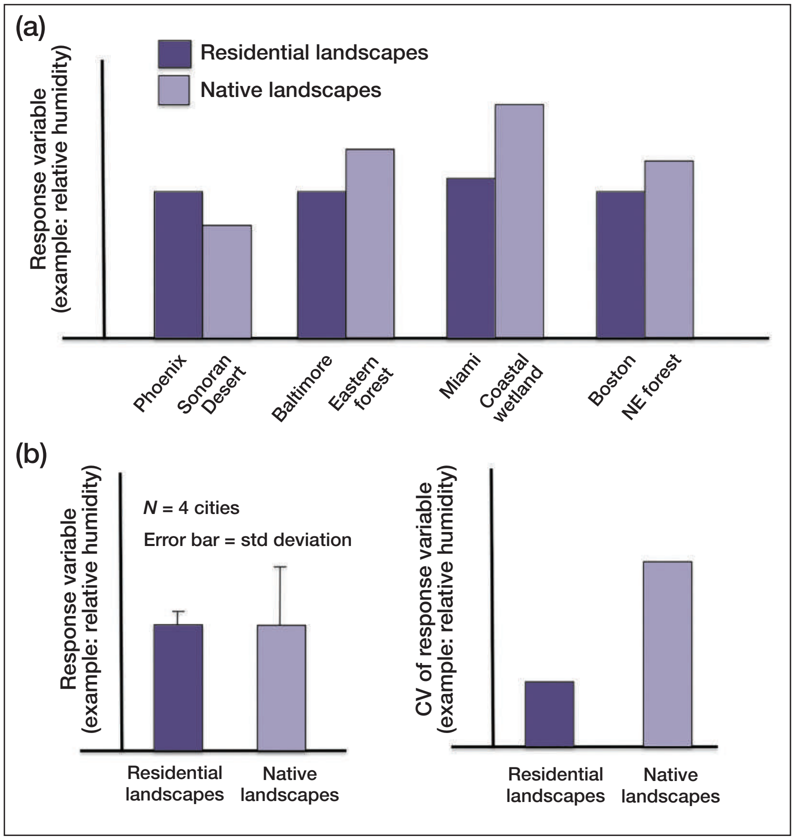

Figure 1. *Hypothesized ecological structure in residential landscapes across four US cities, showing that (a) differences between residential and native ecosystems within each city will be greater than the differences between residential ecosystems in different cities and (b) that differences in native ecosystems across the continent will be larger than differences in urban and suburban ecosystems across the continent. CV = coefficient of variation.*

We address these questions and hypotheses in a US National Science Foundation (NSF) funded MacroSystems Biology Program project that includes six metropolitan statistical areas (MSAs) that cover the major climatic regions of the US: Phoenix, AZ; Miami, FL; Baltimore, MD; Boston, MA; Minneapolis–St Paul, MN; and Los Angeles, CA (WebFigure 1). MSAs are defined and delineated by the US Census Bureau and represent a geographical region with a relatively high population density at its core and close economic ties throughout the area. This definition thus encompasses urban, suburban, and exurban areas in each city. Brown *et al.* (2005) defined urban areas as having a housing density greater than 1 unit per 0.4 ha and exurban areas as having a housing density between 1 unit per 0.4 ha and 16.2 ha. The six cities were chosen to provide broad but certainly not comprehensive coverage of the US and to take advantage of existing multidisciplinary socioecological research groups. We tested for homogenization of soils, plants, water, climate, land practices, and environmental views: specifically, soil C and nitrogen (N) pools, plant species, phylogenetic and functional diversity of vegetation, the $\delta^{13}C$ and $\delta^{15}N$ of plants and soils, hydrography and sediment denitrification potential, microclimate (temperature, humidity) and soil moisture, land-cover and land-use practices (eg fertilizer use), and neighborhood and environmental satisfaction.

The emerging field of macrosystems ecology addresses phenomena at subcontinental spatial extents that range from hundreds to a few thousand kilometers, also referred to as regions in some contexts (Heffernan *et al.* 2014; Levy *et al.* 2014). A hallmark of this field is the study of how macroscale components interact and vary over temporal extents ranging from decades to centuries to millennia. Here, we studied both regional-scale (MSA) and continental-scale (contiguous US) macrosystems and scaling from the household parcel (ecosystem) to the neighborhood (landscape) to the MSA (region) and ultimately to the continent. We focused on urbanization as a key macroscale driver of local and regional ecology that largely overrides natural climate and ecological drivers and produces macroscale (continental-scale) changes. At the household/parcel scale, we coupled homeowner surveys with intensive biophysical measurements to determine how land-management practices influence ecological structure (eg vegetative communities) and function (eg soil biogeochemistry) and vice versa. We compiled extensive, high-resolution (≤ 1.0-m pixels), remotely sensed, and sociodemographic data to assess the extent and spatial distribution of lawns and other cover types at the parcel and neighborhood levels. These data are being used to link personal preferences/decisions and social lifestyles with ecological patterns and processes at broader (MSA) geographic scales. Conducting these MSA-scale

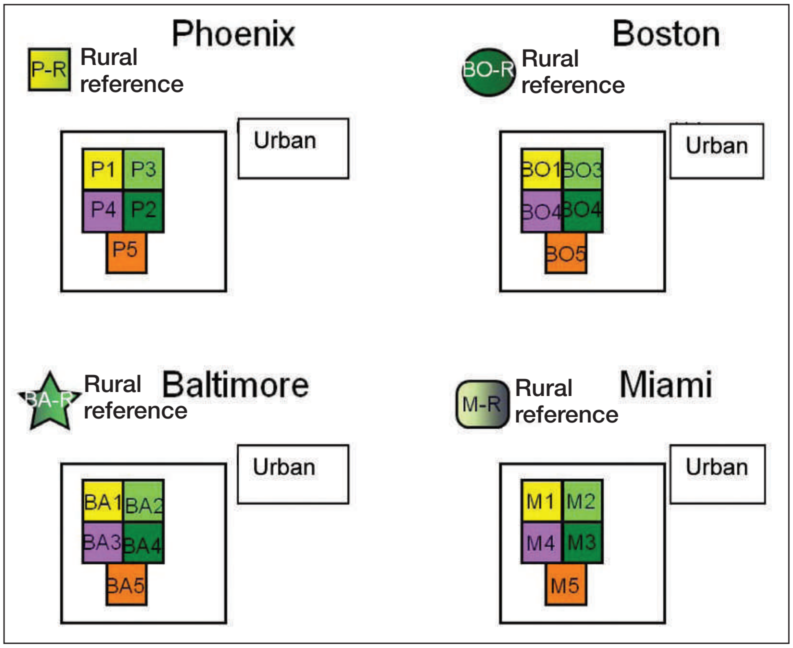

Figure 2. *All cities have neighborhoods with different lifestyle characteristics and landscaping but there is some convergence in the distribution of neighborhood types within cities across the continent. We therefore hypothesize that neighborhoods with similar lifestyle characteristics across different cities will have more similar landscaping preferences and practices than nearby neighborhoods with differing lifestyle characteristics within the same city; for example, yellow neighborhoods in different cities (P1, BO1, BA1, M1) are more similar than yellow and green neighborhoods within a city (eg P1 versus P2 and P3). Small squares represent neighborhoods within cities; numbers and colors correspond to neighborhoods with differing lifestyle characteristics.*

analyses across diverse regions of the US allowed us to determine whether scaling tools based on parcel-level data could be used to produce a continental-scale assessment of the drivers and effects of urban homogenization on ecosystem structure and function. Below, we review the basis for our hypotheses and present preliminary results on the multi-factor, socioecological homogenization of urban USA and its continental-scale applications.

■ The soil and plant ecology of residential landscapes

Perhaps the most obvious aspect of urban/suburban land-use change is the replacement of natural vegetation assemblages by turfgrass yards, popular plant species and horticultural varieties, and impervious surfaces. Within suburban parcels, lawns (or, in arid regions, "xeric" yards with gravel cover and drought-tolerant plants) are the dominant land cover (Robbins and Birkenholtz 2003). Despite concern about the effects of lawn irrigation and fertilization on air and water quality (Robbins *et al.* 2001), considerable uncertainty remains about the environmental performance of lawns (eg stormwater runoff, C and N dynamics). Lawns can have high N losses, especially if over-fertilized and over-watered (Petrovic 1990; Townsend-Small and Czimczik 2010). But lawns have also been shown to have considerable potential for N retention (Gold *et al.* 1990; Raciti *et al.* 2008) and C sequestration (Kaye *et al.* 2005; Golubiewski 2006; Raciti *et al.* 2011).

Although the ability of urban and suburban soils to accumulate C is well established (Pouyat *et al.* 2006), there is greater uncertainty about the amount of aboveground C in residential areas. On average, one-third of urban land in the northeast US is covered by trees and their canopies (Dwyer *et al.* 2000; Nowak and Crane 2002). Analysis with the Urban Forest Effects (UFORE) model suggests that woody biomass in "urban" areas (as defined by the US Census Bureau) sequesters 0.8 megagrams of C per hectare per year (Mg C ha^{-1} yr^{-1}) (Nowak and Crane 2002), or about 71% of the average amount stored annually per hectare in live trees on US forestland (1.12 Mg C ha^{-1} yr^{-1}) (Birdsey 1992).

We suggest that urban/suburban land-use change increases C sequestration at the continental scale. This increase occurs because in arid regions both soil and vegetation C stocks are increased by urbanization, whereas in humid regions, C stocks in unpaved soils (the largest reservoir) are either increased or unchanged by urbanization. We hypothesize that these soil effects are larger than any declines in vegetation C in humid regions, resulting in a net continental increase in ecosystem C stocks.

A comparison of data from Groffman *et al.* (2009) and Zhu *et al.* (2006) regarding soil organic matter and soil moisture levels in Baltimore and Phoenix supports this hypothesis (Figure 3). There is obvious evidence of urban convergence and homogenization, where differences in organic matter and moisture are smaller between any two cities' urban/suburban ecosystems than between a given city and its native ecosystem. Land-use conversion from native cover types to suburban use caused these variables to decrease in humid Baltimore and to increase in arid Phoenix, resulting in homogenization. The decline in organic matter in the suburban residential area (9%) in Baltimore relative to forest was small as compared with the increase associated with conversion to suburban residential ecosystems in Phoenix (52%). These results suggest that in addition to homogenization, conversion of native to residential ecosystems may result in an increase in soil C pools at the continental scale, depending on the relative extents of C-enhanced arid and C-depleted humid residential areas across the continent. More importantly, additional analyses will be required to determine if increases in soil C associated with residential development are supplemented or decreased by changes in vegetation C.

Lawns and residential landscapes contain turfgrass, numerous exotic and native herbaceous species (includ-

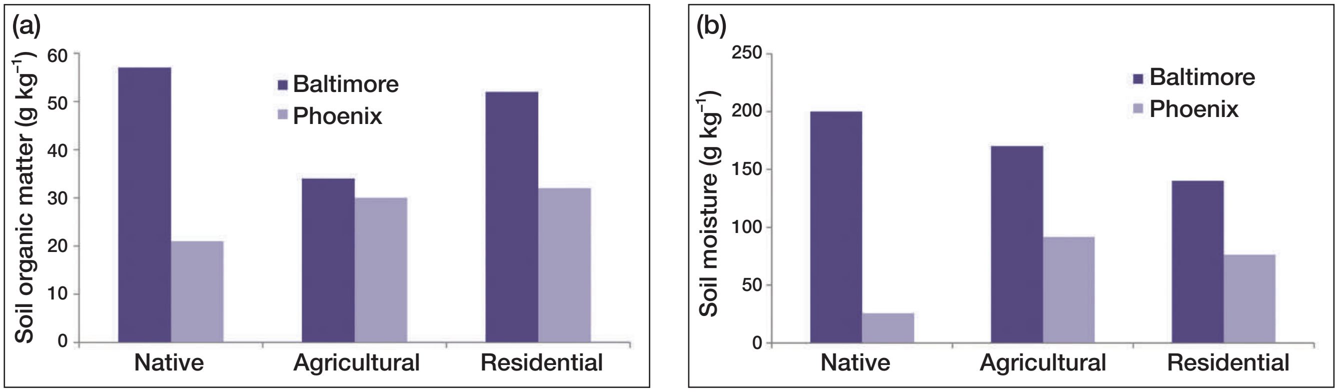

Figure 3. *(a) Soil organic matter and (b) soil moisture in native, agricultural, and suburban residential ecosystems in Baltimore and Phoenix. For both variables, differences between the cities are smaller in agricultural and residential ecosystems than in native ecosystems. Note that data are not corrected for differences in soil depth or density. However, as density is generally increased by residential development, this correction would likely increase the estimates of soil C storage in residential ecosystems relative to the natural ecosystems that they replaced. Baltimore data from Groffman* et al. *(2009) and Phoenix data from Zhu* et al. *(2006).*

ing those designated as "weeds"), and a variety of trees and shrubs. These plant assemblages contribute to the overall managed and emergent diversity of urban landscapes and reflect social and structural drivers of landscaping decisions. We hypothesize that differences in plant community composition and aboveground biomass between biophysically dissimilar regions are reduced by urbanization because residential areas in different regions have more similar landscaping, and therefore plant community composition, relative to the composition of native ecosystems in these regions. More specifically, across regions, we hypothesize that the urban flora will have lower turnover in species and phylogenetic composition than the native flora. Previous research has shown that within a region, on average, the urban flora will have higher species richness but lower phylogenetic diversity than the flora in natural areas resulting from the high number of exotic urban species from relatively few phylogenetic lineages (Figure 4).

Much of the ecological homogenization of urban and suburban ecosystems is likely related to human modification and homogenization of microclimate in cities. For example, comparing differences in monthly average maximum air temperature between urban and rural locations within the Baltimore and Phoenix MSAs demonstrates that while Baltimore generally exhibits urban heating, Phoenix shows urban cooling because of the presence of irrigated landscapes and urban trees (WebFigure 2; Brazel *et al.* 2000). Thus, microclimate is more similar in residential ecosystems in Baltimore and Phoenix than in the native forest and desert ecosystems that previously covered these areas.

The hydrography of residential landscapes

Human alteration of residential landscapes often involves substantial modification of the structure, distribution, and character of surface-water systems, including the intro-

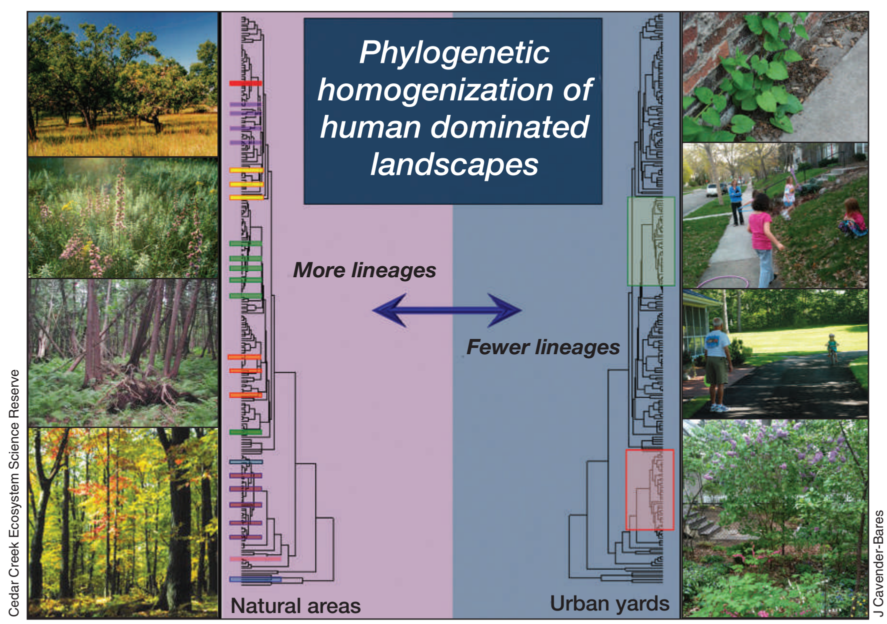

Figure 4. *Phylogenetic diversity in 137 privately managed yards ("urban yards") along a gradient of housing density in the Minneapolis–St Paul metropolis, Minnesota, US, and in a "natural area" at the nearby Cedar Creek Ecosystem Science Reserve. Although yards had more species per hectare than natural areas, yard species were more closely related to each other and had lower phylogenetic diversity. The high number of exotic yard species increased the yard flora's phylogenetic relatedness in comparison to species at Cedar Creek, causing phylogenetic homogenization within yards. The urban environment and homeowners' preferences select for trait attributes and phylogenetic lineages that can colonize and persist in yards. As yard species disperse beyond household boundaries, their functional attributes will affect ecosystem processes in urban environments and beyond. Photo and design: J Cavender-Bares based on results from Knapp* et al. *(2012).*

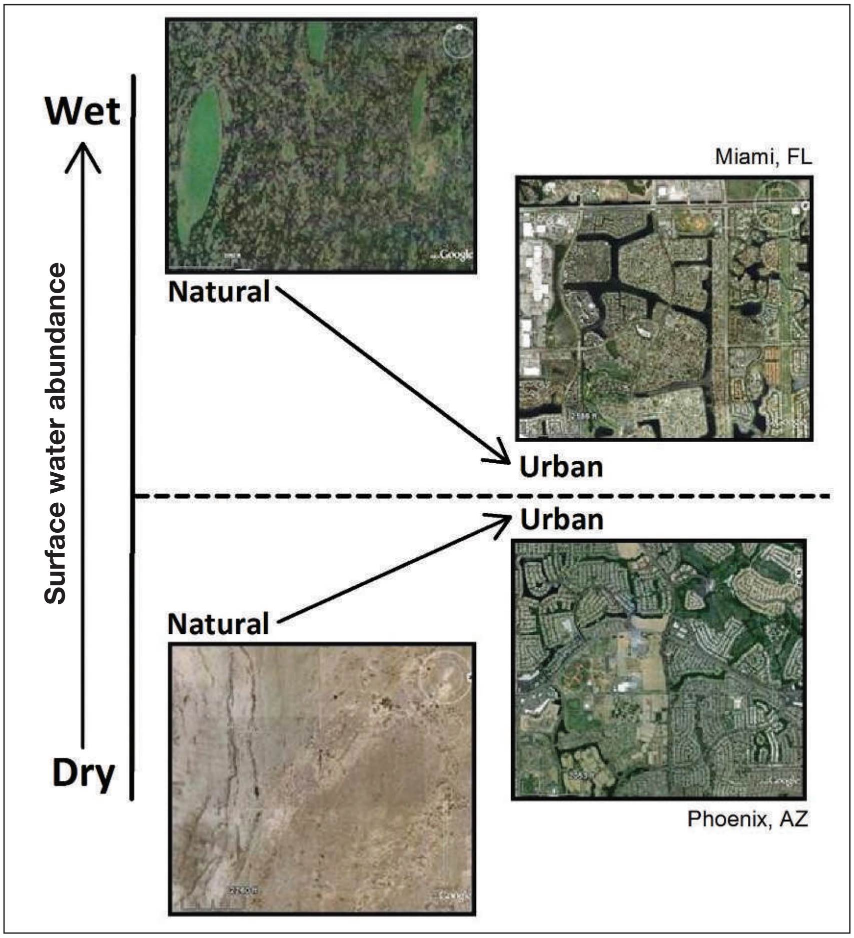

Figure 5. *Urban homogenization should lead to a decrease or alteration in surface waterbodies in humid regions (eg Miami) and an increase in arid regions (eg Phoenix), such that the hydrography of urban ecosystems in these diverse regions are more similar than the hydrography of the native ecosystems that they replaced.*

duction of novel aquatic ecosystems where they were absent and eliminating, or altering, others where they were abundant. Urbanization in mesic temperate zones frequently leads to large-scale loss of channel networks (Elmore and Kaushal 2008; Roy *et al.* 2009). Residential development in Phoenix has included the construction of lakes and canals for flood control and recreation (Roach *et al.* 2008; Larson and Grimm 2012); in Miami, urban expansion into wetlands requires construction of lakes to provide drainage and fill (Figure 5). As a result, the hydrography of residential neighborhoods in Miami and Phoenix is more similar to each other than to the hydrography of the Sonoran Desert and Everglades natural ecosystems that they replaced.

We hypothesize that hydrographic change associated with urban development is shaped by interactions among economic pressures for land development and use, engineering necessities resulting from local hydrogeologic conditions, and preferences for particular aesthetics and portfolios of ecosystem services. We therefore expect urban hydroscapes to converge on a moderate-to-low density of surface water, reflecting the elimination and addition of waterbodies in wet and dry regions, respectively.

In addition to these landscape-scale changes, urban waterbodies also exhibit notable changes in physical and biological structure and ecosystem-scale processes. In streams, where the effects of urbanization are best studied, "urban stream syndrome" describes a suite of changes, including bigger differences between high storm flows and low "base" flows, reduced channel complexity, nutrient enrichment, and loss of species diversity (Walsh *et al.* 2005). There is also great interest in the landscape- or system-scale effects of urbanization on lakes. For example, do the shapes of urban lakes differ from those in undeveloped areas as a result of modification of existing waterbodies or construction of new ones? How different are hydrologic connections to uplands and channel networks? Do these effects depend on lake size? Are parameters such as denitrification potential, invertebrate communities, or nutrient cycling homogenized by urbanization?

■ Land management and ecology at the parcel and neighborhood scales

The fundamental actors in residential land management are individual residents and the household units to which they belong. Household decision makers maintain their yards in particular ways for a variety of reasons, affecting the structure and function of urbanized ecosystems and associated element fluxes in complex ways. Understanding and mapping parcel-scale dynamics is therefore critical to evaluating the impact of residential land management on ecosystem structure and function at large scales. Technological and methodological advances have greatly facilitated a multi-scalar approach to residential landscape change and homogenization. Until recently, available data included only coarse geospatial land-cover information or US Census block-group or tract data, aggregating 200–400 or 2500–8000 households respectively. New methods have been developed for mapping ecological structure (eg the distribution of grass, trees, and shrubs) at the highly detailed parcel scale over large areas. In addition, understanding historical and contemporary processes of residential land management (eg fertilizer use) can benefit from social science theories that address environmental decisions at varying spatial scales, ranging from individual behavior to broader forces at neighborhood, city, and regional scales (Roy Chowdhury *et al.* 2011; Cook *et al.* 2012; Fissore *et al.* 2012). More generally, homogenization is driven by human habitat preferences, as expressed through socioeconomic factors and lifestyles. Development of a more general theory and science of human habitats, comparable to the study of other species' habitats, would help in understanding these processes.

A growing body of research focuses on the social factors affecting variation in residential land management in urban areas. Such management depends on residents' aesthetic values, experience, and economics but is also affected by wider hierarchical structures, such as neighborhood norms and rules, watershed-level ecological context, land and commodity markets, and municipal-, state-, and national-level policies (Zhang *et al.* 2013). We contend that residential land management can be better understood by integrating distinct, overlapping theories of (sub)urban development and change pertaining to at least three fundamental social-organizational scales: individual/household decisions, neighborhood-level processes, and regional-scale policy institutions. Theories operating at these three scales address (but are not limited to) formal and informal governance institutions and property regimes (eg land ownership and tenure rights, cultural customs and expectations), demographic and political economic factors, social stratification, and lifestyle-based and individual attitudinal differences. At the scale of households and parcels, attitudinal factors, household demographics, life stage and lifestyle, and additional spatial and biophysical parcel characteristics combine in complex ways to produce residential landscapes at the local scale. Neighborhood social dynamics and composition, including local and historical traditions, are also critical to the progression of residential landscapes. At the regional scale, municipal and state regulatory structures respond to processes and predictions of urban growth with zoning codes and land-use regulations that directly prescribe lot sizes and in some cases the amount and kind of impervious and vegetative cover. Regional-scale policies are in turn influenced by national and broader-scale dynamics and institutions, including market fluctuations, federal policies, and the global economy.

Several studies have used measures of income and education to examine the relationship between socioeconomic status and vegetation cover (Grove and Burch 1997; Dow 2000; Martin *et al.* 2004). More recently, the emergent social–ecological research discipline has addressed relationships between households, their lifestyle behaviors, and their environmental impacts (Grove *et al.* 2006; Troy *et al.* 2007; Boone *et al.* 2009; Zhou *et al.* 2009). A critical finding from this body of research is that lifestyle factors – such as family size, life stage, and ethnicity – may be weakly correlated with socioeconomic status but nevertheless play a crucial role in determining how households manage their properties in various neighborhoods.

In a preliminary analysis, land-cover composition within a sample of 87 census block-groups across Baltimore, Boston, and Miami, from two contrasting social/lifestyle groups – an urban, high affluence group (S07) and an exurban, low affluence group (S48) – displayed complex patterns of similarities and differences within and between the three cities (WebFigure 3). Tree cover (> 50%) and impervious surface proportions (8–11%) in sampled S07 neighborhoods in Boston and Baltimore were very similar, though relative grass cover in Baltimore was more than double that in Boston. Miami's S07 neighborhoods diverged from this pattern, displaying far greater proportions (50%) of grass and impervious surface (15%) and less proportional tree cover (23%). S48 neighborhoods in Boston and Miami had similar proportions of impervious (14–16%) and other (12–17%) covers, but markedly distinct proportions of grass (greater in Miami) and tree cover (greater in Boston). "Other", mainly bare soil and water, refers to land cover that does not fit into the remaining categories. Sampled neighborhoods therefore appear to demonstrate homogenization of certain land covers for Baltimore and Boston (especially for S07) and for Boston and Miami (especially for S48).

A sample of exurban, low affluence neighborhoods (S48) in Baltimore and Boston had a higher percentage of impervious cover than their urban, affluent counterparts (S07) in each city (supporting expectations of distinct lifestyle groups being associated with distinct land-cover outcomes *within* each city). In Baltimore, sampled S07 and S48 neighborhoods diverged in their relative proportions of tree and grass cover, with the former group maintaining larger portions in each. Miami's sampled S07 and S48 neighborhoods did not display marked differences, belying expectations of distinct landscape/land-cover outcomes for distinct lifestyle neighborhood groups. The same appears to be true for tree and grass cover in sampled neighborhoods in Boston.

Sample results are partially consistent with expectations of similar lifestyle groups/neighborhoods displaying similar land-cover patterns across cities. Further analysis of additional cities is necessary to determine whether there are clear patterns of convergence by lifestyle group, especially when confounding, multi-scalar factors are controlled for (eg in multi-level statistical models of land-cover and land-management practices). We expect the degree of convergence to differ by domain (eg type of land cover, particular indices of landscape structure, etc).

As important as it is to compare land *cover* within and across MSAs in the US, a comprehensive test of the homogenization hypothesis requires a comparison of land *use*. Our project has collected extensive measures of land management (eg fertilizer application, contracting with professional lawncare companies), using various means. In November 2011, we completed a telephone survey of ~9500 households, using a stratified random sampling design, roughly equally divided among the six cities. Yet such survey instruments offer only a partial view of the subtleties associated with the complex land-use decision-making process. Given that open-ended, qualitative interviews with homeowners may provide this additional level of detail (Harris *et al.* 2012, 2013), we are conducting ~200 in-person interviews with homeowners, again roughly evenly divided among these six cities and again using a stratified random sampling design.

Conclusions

Urbanization, and the forms of ecological homogenization that it causes, is a central topic in the emerging field of macrosystems ecology. Ecological changes – in soil; in plant diversity, composition, and structure; and in microclimate and hydrography – across broad areas of North America, and indeed around the world, are influenced by a finite set of human drivers that apply over local-scale (parcels and neighborhoods), regional-scale (MSA) and continental-scale (US) macrosystems. Understanding this homogenization should fundamentally improve our ability to study ecological processes and their anthropogenic and geophysical drivers at comparable resolution, using data that are multi-scale, multi-variate, and multithematic (ie to carry out macrosystems ecology). Moreover, our analysis will provide insight into urban homogenization, which strongly influences not only environmental change at continental scales but also the quality of life for most of the world's human population.

Acknowledgements

We thank the MacroSystems Biology Program in the Emerging Frontiers Division of the Biological Sciences Directorate at NSF for support. The "Ecological Homogenization of Urban America" project was supported by a series of collaborative grants from this program (EF-1065548, 1065737, 1065740, 1065741, 1065772, 1065785, 1065831, 121238320). The work arose from research funded by grants from the NSF Long Term Ecological Research Program supporting work in Baltimore (DEB-0423476), Phoenix (BCS-1026865, DEB-0423704 and DEB-9714833), Plum Island (Boston) (OCE-1058747 and 1238212), Cedar Creek (Minneapolis–St Paul) (DEB-0620652), and Florida Coastal Everglades (Miami) (DBI-0620409). B Michener, S Faulkner, S Arnott, and B Wee provided helpful comments on earlier drafts of the manuscript. For author contributions, see WebPanel 1.

References

Birdsey RA. 1992. Carbon storage and accumulation in United States forest ecosystems. General technical report WO-59. Washington, DC: USDA Forest Service.

Boone C, Cadenasso M, Grove J, *et al.* 2009. Landscape, vegetation characteristics, and group identity in an urban and suburban watershed: why the 60s matter. *Urban Ecosystems* **13**: 255–71.

Brazel A, Selover N, Vose R, and Heisler G. 2000. The tale of two climates – Baltimore and Phoenix urban LTER sites. *Clim Res* **15**: 123–35.

Brown DG, Johnson KM, Loveland TR, and Theobald DM. 2005. Rural land-use trends in the conterminous United States, 1950–2000. *Ecol Appl* **15**: 1851–63.

Cook EM, Hall SJ, and Larson KL. 2012. Residential landscapes as social–ecological systems: a synthesis of multi-scalar interactions between people and their home environment. *Urban Ecosystems* **15**: 19–52.

Dow K. 2000. Social dimensions of gradients in urban ecosystems. *Urban Ecosystems* **4**: 255–75.

Dwyer J, Nowak D, Noble M, and Sisinni S. 2000. Connecting people with ecosystems in the 21st century: an assessment of our nation's urban forests. General technical report PNW-GTR-490. Portland, OR: USDA Forest Service Pacific Northwest Research Station.

Elmore AJ and Kaushal SS. 2008. Disappearing headwaters: patterns of stream burial due to urbanization. *Front Ecol Environ* **6**: 308–12.

Fissore C, Hobbie S, King J, *et al.* 2012. The residential landscape: fluxes of elements and the role of household decisions. *Urban Ecosystems* **15**: 1–18.

Foley JA, DeFries R, Asner GP, *et al.* 2005. Global consequences of land use. *Science* **309**: 570–74.

Gold AJ, Deragon WR, Sullivan WM, and Lemunyon JL. 1990. Nitrate-nitrogen losses to groundwater from rural and suburban land uses. *J Soil Water Conserv* **45**: 305–10.

Golubiewski NE. 2006. Urbanization increases grassland carbon pools: effects of landscaping in Colorado's Front Range. *Ecol Appl* **16**: 555–71.

Grimm NB, Foster D, Groffman P, *et al.* 2008. The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. *Front Ecol Environ* **6**: 264–72.

Groffman PM, Williams CO, Pouyat RV, *et al.* 2009. Nitrate leaching and nitrous oxide flux in urban forests and grasslands. *J Environ Qual* **38**: 1848–60.

Grove JM and Burch WR. 1997. A social ecology approach to urban ecosystems and landscape analysis. *Urban Ecosystems* **1**: 185–99.

Grove JM, Troy AR, O'Neil-Dunne JPM, *et al.* 2006. Characterization of households and its implications for the vegetation of urban ecosystems. *Ecosystems* **9**: 578–97.

Harris EM, Martin DG, Polsky C, *et al.* 2013. Beyond "lawn people": the role of emotions in suburban yard management practices. *Prof Geogr* **65**: 345–61.

Harris EM, Polsky C, Larson K, *et al.* 2012. Heterogeneity in residential yard care: evidence from Boston, Miami, and Phoenix. *Hum Ecol* **40**: 735–49.

Heffernan JB, Soranno PA, Angilletta MJ, *et al.* 2014. Macrosystems ecology: understanding ecological patterns and processes at continental scales. *Front Ecol Environ* **12**: 5–14.

Katz B, Lang RE, and Berube A (Eds). 2003. Redefining urban and suburban America: evidence from Census 2000. Washington, DC: Brookings Institution Press.

Kaye JP, McCulley RL, and Burke IC. 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. *Glob Change Biol* **11**: 575–87.

Knapp S, Dinsmore L, Fissore C, *et al.* 2012. Phylogenetic and functional characteristics of household yard floras and their changes along an urbanization gradient. *Ecology* **93**: S83–S98.

Larson E and Grimm N. 2012. Small-scale and extensive hydrogeomorphic modification and water redistribution in a desert city and implications for regional nitrogen removal. *Urban Ecosystems* **15**: 71–85.

Larson KL, Cook E, Strawhacker C, and Hall SJ. 2010. The influence of diverse values, ecological structure, and geographic context on residents' multifaceted landscaping decisions. *Hum Ecol* **38**: 747–61.

Levy O, Ball BA, Bond-Lamberty B, *et al.* 2014. Approaches to advance scientific understanding of macrosystems ecology. *Front Ecol Environ* **12**: 15–23.

Martin CA, Warren PS, and Kinzig A. 2004. Neighborhood socioeconomic status is a useful predictor of perennial landscape vegetation in small parks surrounding residential neighborhoods in Phoenix, Arizona. *Landscape Urban Plan* **69**: 355–68.

McKinney ML. 2006. Urbanization as a major cause of biotic homogenization. *Biol Conserv* **127**: 247–60.

Nowak D and Crane D. 2002. Carbon storage and sequestration by urban trees in the United States. *Environ Pollut* **116**: 381–89.

Petrovic AM. 1990. The fate of nitrogenous fertilizers applied to turfgrass. *J Environ Qual* **19**: 1–14.

Pickett STA, Cadenasso ML, Grove JM, *et al.* 2011. Urban ecological systems: scientific foundations and a decade of progress. *J Environ Manage* **92**: 331–62.

Pouyat RV, Belt KT, Pataki DE, *et al.* 2007. Urban land-use change effects on biogeochemical cycles. In: Canadell P, Pataki DE, and Pitelka L (Eds). Terrestrial ecosystems in a changing world. Berlin, Germany: Springer-Verlag.

Pouyat RV, Yesilonis ID, and Nowak DJ. 2006. Carbon storage by urban soils in the United States. *J Environ Qual* **35**: 1566–75.

Raciti SR, Groffman PM, and Fahey TJ. 2008. Nitrogen retention in urban lawns and forests. *Ecol Appl* **18**: 1615–26.

Raciti SR, Groffman PM, Jenkins JC, *et al.* 2011. Accumulation of carbon and nitrogen in residential soils with different land use histories. *Ecosystems* **14**: 287–97.

Roach WJ, Heffernan JB, Grimm NB, *et al.* 2008. Unintended consequences of urbanization for aquatic ecosystems: a case study from the Arizona desert. *BioScience* **58**: 715–27.

Robbins P and Birkenholtz T. 2003. Turfgrass revolution: measuring the expansion of the American lawn. *Land Use Policy* **20**: 181–94.

Robbins P, Polderman A, and Birkenholtz T. 2001. Lawns and toxins: an ecology of the city. *Cities* **18**: 369–80.

Roy AH, Dybas AL, Fritz KM, and Lubbers HR. 2009. Urbanization affects the extent and hydrologic permanence of headwater streams in a midwestern US metropolitan area. *J N Am Benthol Soc* **28**: 911–28.

Roy Chowdhury R, Larson K, Grove JM, *et al.* 2011. A multi-scalar approach to theorizing socio-ecological dynamics of urban residential landscapes. *Cities Environ* **4**: art 6. http://digitalcommons.lmu.edu/cate/vol4/iss1/6. Viewed 23 Dec 2013.

Townsend-Small A and Czimczik CI. 2010. Carbon sequestration and greenhouse gas emissions in urban turf. *Geophys Res Lett* **37**: L02707.

Troy AR, Grove JM, O'Neil-Dunne JPM, *et al.* 2007. Predicting opportunities for greening and patterns of vegetation on private urban lands. *Environ Manage* **40**: 394–412.

Walsh CJ, Roy AH, Feminella JW, *et al.* 2005. The urban stream syndrome: current knowledge and the search for a cure. *J N Am Benthol Soc* **24**: 706–23.

Zhang C, Wu J, Grimm NB, *et al.* 2013. A hierarchical patch mosaic ecosystem model for urban landscapes: model development and evaluation. *Ecol Model* **250**: 81–100.

Zhou WQ, Troy A, Grove JM, and Jenkins JC. 2009. Can money buy green? Demographic and socioeconomic predictors of lawn care expenditures and lawn greenness in urban residential areas. *Soc Nat Resour* **22**: 744–60.

Zhu WX, Hope D, Gries C, and Grimm NB. 2006. Soil characteristics and the accumulation of inorganic nitrogen in an arid urban ecosystem. *Ecosystems* **9**: 711–24.

[5]*Nicholas School of the Environment, Duke University, Durham, NC;* [6]*Schools of Geographical Sciences and Urban Planning and Sustainability, Arizona State University, Tempe, AZ;* [7]*The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA;* [8]*Department of Forest Resources and Department of Fisheries, Wildlife, and Conservation Biology, University of Minnesota, St Paul, MN;* [9]*Spatial Analysis Lab, Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT;* [10]*Department of Global and Sociocultural Studies, University Park Campus, Florida International University, Miami, FL;* [11]*Department of Biology, University of Utah, Salt Lake City, UT;* [12]*Graduate School of Geography, Clark University, Worcester, MA;* [13]*Department of Geography, Indiana University, Bloomington, IN*