Beyond Urban Legends: An Emerging Framework of Urban Ecology, as Illustrated by the Baltimore Ecosystem Study

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The emerging discipline of urban ecology is shifting focus from ecological processes embedded within cities to integrative studies of large urban areas as biophysical-social complexes. Yet this discipline lacks a theory. Results from the Baltimore Ecosystem Study, part of the Long Term Ecological Research Network, expose new assumptions and test existing assumptions about urban ecosystems. The findings suggest a broader range of structural and functional relationships than is often assumed for urban ecological systems. We address the relationships between social status and awareness of environmental problems, and between race and environmental hazard. We present patterns of species diversity, riparian function, and stream nitrate loading. In addition, we probe the suitability of land-use models, the diversity of soils, and the potential for urban carbon sequestration. Finally, we illustrate lags between social patterns and vegetation, the biogeochemistry of lawns, ecosystem nutrient retention, and social-biophysical feedbacks. These results suggest a framework for a theory of urban ecosystems.

Keywords: city, coupled natural-human system, patch dynamics, social-ecological system, urban ecosystem

Urban ecology is emerging as an integrated science (Grimm et al. 2000). It aims to understand extensive urban areas that include not only biological and physical features but also built and social components (Cadenasso et al. 2006a). Its breadth and inclusive ecological perspective differentiate the current status of urban ecology from its earlier incarnations (Pickett et al. 2001). In the early 20th century, ecological factors were used to explain specific urban processes, such as the spread of disease in cities, and concepts of ecological succession and zonation were adopted to explain the competition between different social groups and the spatial layout of neighborhoods (Park and Burgess 1925). By the middle of the last century, ecologists had begun to apply the ecosystem perspective to cities to estimate urban material

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budgets (e.g., Boyden et al. 1981). Stearns (1970) made a notable effort to bring urban ecology within the fold of mainstream ecology. However, it has taken the intervening period for the supporting conceptual frameworks to develop (Cadenasso et al. 2006b), the interdisciplinary dialogs to mature, and the empirical base to broaden sufficiently for urban research to take shape as a inclusive and rigorous field of ecological study, and to exhibit its potential for integrating with other disciplines in the physical and social sciences (Pickett et al. 2001).

This disciplinary maturity and utility has been facilitated by the investment of the National Science Foundation (NSF), the USDA (US Department of Agriculture) Forest Service, and partner institutions in major urban ecological research projects. The Baltimore Ecosystem Study (BES), part of the NSF's Long Term Ecological Research Network, is one such project. We briefly summarize a diverse range of research findings from the BES that exemplify the state of the art of contemporary urban ecology. We use these findings to clarify assumptions about urban ecological systems and to address this question: Is existing ecological theory sufficient to support the new discipline of integrated urban ecology, or is new theory required (Collins et al. 2000)? Articulating and evaluating key assumptions about complex urban regions as integrated social-ecological systems can help contribute to a preliminary theoretical framework.

The need for better understanding of urban ecosystems emerges from two trends. First, cities are home to an increasing fraction of humanity. Hence, most people's experience of nature is urban (Miller 2005). Therefore, settled ecosystems must be better used to exemplify environmental principles (Berkowitz et al. 2003). Second, urban lands have a disproportionate impact on regional and global systems (Collins et al. 2000). The sprawl of many cities consumes agricultural lands and threatens the integrity of neighboring wild and managed areas (Berube and Forman 2001). Some 110,000 square kilometers in the United States are impervious (Elvidge et al. 2004), and urban land cover affects a much larger area through alteration of climate, atmospheric chemistry, and hydrology (Pickett et al. 2001). All these facts point to the need for better understanding of urban ecosystems, and for improvement of the theory to explain and predict their dynamics.

We present 12 findings from the BES that illustrate the growth of urban ecological knowledge. We have chosen examples that illustrate new assumptions about urban systems or question assumptions that ecologists sometimes make. These findings include several results that our team did not anticipate. The findings help frame a series of gradients over which comparative studies of different cities or time periods can be conducted. In this way, we suggest a new framework or paradigm for urban ecological research. (Complete literature citations for each example are available online at *http://ecostudies.org/urban_legends/refs.pdf.*)

The Baltimore Ecosystem Study

Research in the BES works toward the overall goal of understanding the patch dynamics of a human ecosystem. Patch dynamics are the patterns and changes in hierarchical spatial heterogeneity and the effects of this heterogeneity on ecosystem function. The study of patch dynamics integrates the biophysical and social components of the human ecosystem. To investigate patch dynamics, the BES addresses three questions broadly relevant to all disciplines that contribute to an integrated urban ecology:

1. How do the spatial structures of the socioeconomic, ecological, and physical features of an urban area relate to one another, and how do they change through time?

2. What are the fluxes of energy, of matter, and of human, built, and social capital in an urban system; how do they relate to one another; and how do they change over the long term?

3. How can people develop and use an understanding of the metropolis as an ecological system to improve the quality of their environment, and to reduce pollution to downstream air- and watersheds?

The first question addresses the social and biophysical patterns of the urban ecosystem in time and space, while the second question addresses the key social and biophysical processes within the system, as well as those that link the system with the larger world. Together, questions 1 and 2 address the relationship of the structure of the urban ecosystem to its function. Question 3 addresses the importance of the flux of information within the urban ecosystem, and recognizes that scientific research within a city cannot be independent of the knowledge and activities that exist there. Consequently, we address the feedback of ecological knowledge—both the knowledge generated by our project and that generated by the educational, management, and policy communities—on the ecology of the Baltimore region. The research findings we report reflect the three guiding questions (figure 1).

The study area includes the city of Baltimore and its five surrounding counties (*http://beslter.org*). Baltimore City is home to 651,154, while the population of the Baltimore–Towson metropolitan area is 2,552,994 (US Census Bureau 2000). Located in the deciduous forest biome, on the Chesapeake Bay estuary, Baltimore City is drained by three major streams and a direct harbor watershed. Several of its watersheds extend into Baltimore County. Socioeconomic studies are keyed to the watersheds and focus on the households and neighborhoods within them, as well as on institutional and spatial aggregations that extend beyond the catchments. Biogeophysical studies focus on the streams as integrators of watershed ecosystem function, including the impact of infrastructure and the built environment. Biogeophysical studies also employ extensive terrestrial sampling points; permanent plots for vegetation, soil organisms, and nutrient processing; and an eddy flux tower to assess atmosphere-

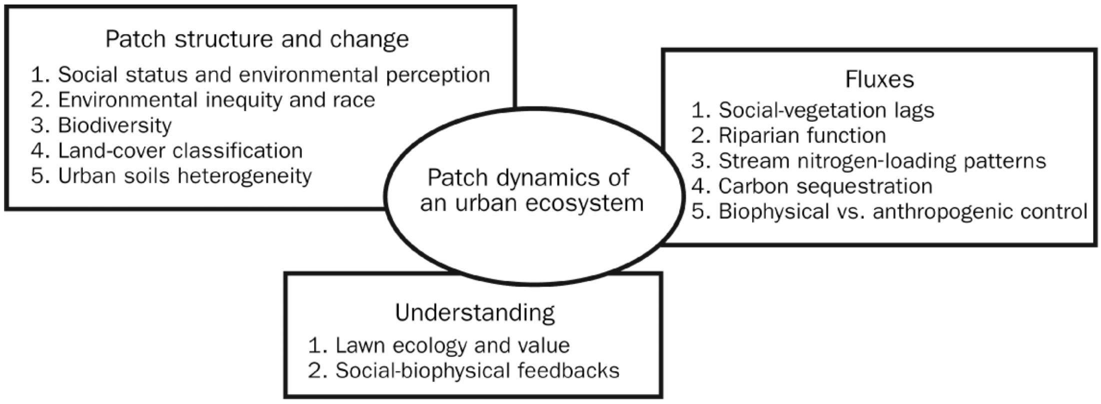

Figure 1. The distribution of the 12 findings relative to the three guiding questions of the Baltimore Ecosystem Study (BES). The overarching goal of the project is shown in the central oval, with the supporting questions linked to it. The findings for question 1 deal with social or biophysical patchiness and, in some cases, with the relationships of social and biophysical features of patchiness. The findings for question 2 deal with fluxes and their controls. Most findings in this area deal with biophysical fluxes, though some reflect fluxes in social capital, or the relationship of biophysical and social fluxes. The findings for question 3 deal with how knowledge or perception of environment is related to social drivers or to actions affecting biophysical processes. Not all research topics in the BES are covered in this survey of findings.

land transfers. A small, forested watershed in Baltimore County serves as a reference.

Social findings

We present two findings representing controversy in the social sciences. Both findings link social processes with environmental perceptions and outcomes.

Finding 1: Class, income, and ethnicity do not always determine perception of environmental problems. Conventional wisdom often holds that concern for environmental quality is concentrated among residents of wealthy, upper-class, predominantly white communities who have transitioned from giving top priority to physical sustenance and can afford to invest in quality of life. Poorer, unempowered, and ethnically mixed communities are assumed to be more preoccupied with satisfying basic needs than with protecting the environment (Inglehart 1989). Limited support for this postmaterialist thesis comes from macro-level international comparisons of affluence (Arrow et al. 1995) in which environmental quality is often interpreted as a "luxury good" to be provided after basic needs are met. However, comparisons of public attitudes across income levels and ethnic groups have also shown that public environmental concern is not restricted to wealthy nations or communities (Brechin and Kempton 1994).

Likewise, BES researchers found that environmental quality issues are of concern to residents in both wealthy and poor urban communities. For example, in a random telephone survey of 1274 residents of the Baltimore region, no statistically significant difference was found across the metropolitan area, with its great range of household income, between resident awareness of or concern about air quality (figure 2). This finding suggests that people in poorer communities actually do perceive a problem when their environment is in poor condition, with concomitant threats to their health. Of course, there may be differential concern among the wealthy, working, or poor classes about other environmentally relevant variables not measured in the survey.

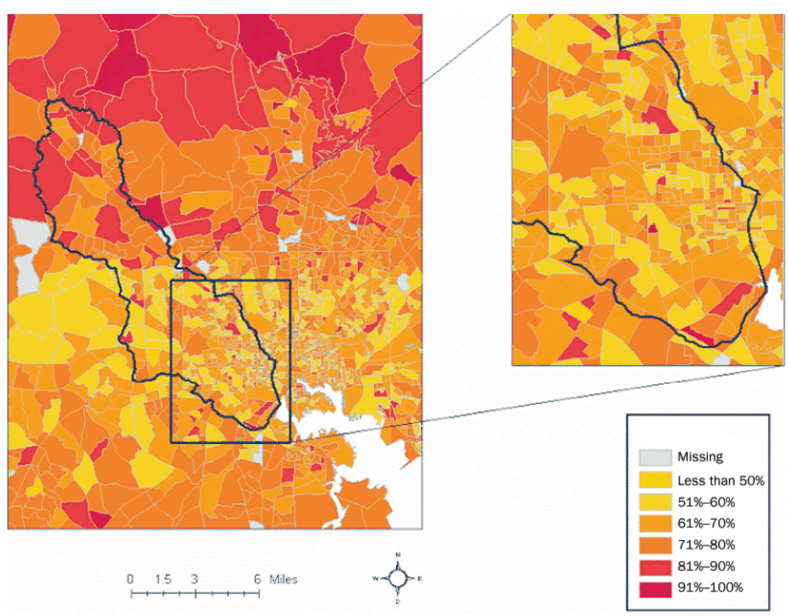

Figure 2. Results of a telephone survey of Baltimore residents, addressing environmental perceptions. Although there is significant spatial differentiation in economic status among the households surveyed, the percentage of residents who agree that air quality is "not a problem" is not significantly different among neighborhoods.

Finding 2: Environmental inequity is not limited to people of color. An often-cited United Church of Christ (1987) study demonstrated that minority groups tend to live near sites with likely health risks, such as hazardous waste facilities and polluting industries. Since that study, scores of others have analyzed the relationship between unwanted land uses and residential neighborhoods. Results have been contradictory; some suggested that race is a factor, but others did not. Yet the perception remains that minorities are more likely to live near facilities that lessen quality of life or pose health risks.

Our work in Baltimore City found the unexpected: whites are more likely than blacks to live near Toxics Release Inventory (TRI) sites (Boone 2002). Although blacks make up 64% of the city's population, census tracts that contain a TRI site have a mean population value of 38% black and 56% white. Using distance buffers and dasymetric mapping of census variables, the results are similar. The pattern in Baltimore City emerges from a long history of residential and occupational segregation. Living close to work in the factories was once an amenity restricted mainly to white Baltimoreans. Because the racial composition of many neighborhoods persists, many of the residences near the TRI sites that were white in the 1940s remain so today. Current relationships between TRI sites and population characteristics may be misleading if legacies are neglected.

Biophysical findings

The results of six studies represent findings motivated by biological ecology. Although these findings focus on the biotic component of urban areas, they have linkages to human behavior or ecosystem services to humans.

Finding 3: The urban biota is diverse. Urbanization is portrayed as a leading threat to global biodiversity, causing the elimination of "the large majority of native species" (McKinney 2002). We do not dispute that important biotic elements are threatened or impaired by urbanization, but such a blanket portrayal implies that the biota of urban and suburban areas is by definition impoverished. Work in Baltimore and other cities shows that habitats in cities are more biotically diverse than is commonly thought (Kühn et al. 2004, Wania et al. 2004). Useful habitat consists not only of large green spaces but also of small pocket parks, vacant lands, and residential yards, among other habitat types (Blair 2004).

In Baltimore, we have found new species of invertebrates (Csuzdi and Szlavecz 2002), populations of rare plants (including two state-level endangered species; Davis 1999), and wide variance in species abundances and levels of biodiversity within the urban matrix (figure 3; Groffman et al. 2006). For example, diverse, native beetle communities exist close to the urban core in large forest parks. The avifauna also contains important diversity. A breeding-season bird survey in 46 random street-side areas within Baltimore City encountered 33% of the 133 regionally breeding, native species in three visits to each site.

Although exotic species are a component of the Baltimore biota, their abundance is taxon and site dependent, and they are not always dominant. For example, abundances of the three most common exotic bird species in Baltimore City are not correlated with one another, a finding not specifically addressed in many previous studies (but see Johnsen and VanDruff 1987, Blair 2004). Thus, the quintessential urban bird

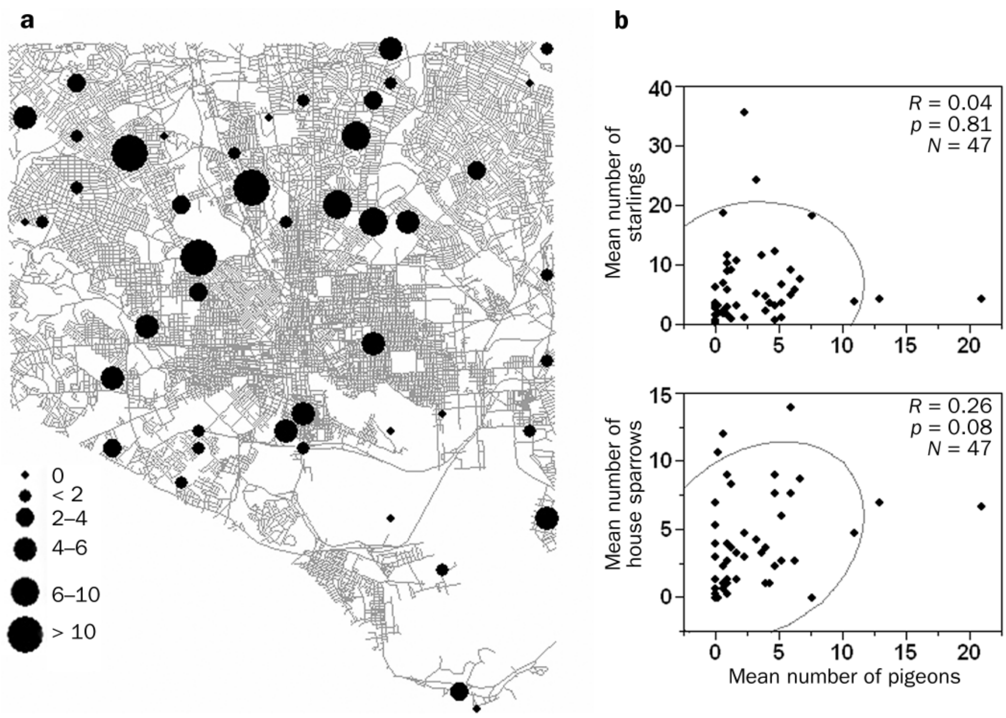

*Figure 3. Variation in the abundance of an exotic bird species, the rock pigeon (*Columba livia*), at random sites in Baltimore. (a) The abundance of exotic bird species is generally agreed to increase with urbanization. Abundances, however, vary considerably within the city. Circles represent mean numbers of individuals over three point counts in May–June 2002. (b) The three exotic urban bird species also appear to occupy different urban habitats. The numbers of rock pigeons are not strongly correlated with those of house sparrows (*Passer domesticus*) and European starlings (*Sturnus vulgaris*). Graphs show pairwise correlations and 90% confidence intervals (curved lines) for mean numbers of individuals detected over three point counts during May–June 2002.*

species—rock pigeons (figure 3a), house sparrows, and European starlings—are each associated with distinct urban habitats (figure 3b). Furthermore, the abundance of these species in different parts of the city ranged from 6% to 93%, and proportions of exotics in invertebrate communities varied from 0% for carrion beetles to 100% for terrestrial isopods. Ninety-five percent of the exotic plant species in riparian areas within Baltimore were neither broadly nor invasively distributed, but instead were only locally abundant.

Our findings in Baltimore are not anomalous. Other urban areas also support important pools of biodiversity (e.g., Blair 2004, Kühn et al. 2004, Kinzig et al. 2005), representing surprisingly large fractions of the regional fauna (e.g., Korsós et al. 2002). Indeed, Wania and colleagues (2004) found that native plant diversity was greater in urban than in nearby rural areas in central Germany.

The discovery that biodiversity in urban areas is often high, and includes at least some endangered, rare, and native species, does not alleviate concern about further introductions of exotic species. Of course, exotic species have been major agents of disruption of ecosystem structure. One concern is that urban areas are biotically homogenous, obliterating expected broadscale differences in diversity (Blair 2004, McKinney 2006, Schwartz et al. 2006). Newly introduced herbivores, such as the hemlock wooly adelgid and the Asian long-horned beetle, threaten the composition and integrity of much natural and managed vegetation. Among soil invertebrates, invasive earthworms have become a major concern because of their ability to alter forest floor composition and nutrient cycling (e.g., Szlavecz et al. 2006). At the same time, exotics may serve as important resources for native species. Earthworms are an important food source for ground-feeding birds. An additional trophic function for exotic species is seen in Davis, California, where 29 of 32 native butterflies breed on nonnative plants, many designated as "weeds" (Shapiro 2002). An assessment of species function is important for both exotic and native species of urban areas. The need to counter the experience deficit for nature in cities is an important function of both native and exotic species (Miller 2005).

Finding 4: Urban riparian areas are not nitrate sinks. Riparian areas are considered hotspots of ecological function in watersheds because of their location at the interface between terrestrial and aquatic patches. Much research has documented that riparian zones prevent the movement of pollutants, in particular nitrate (NO_3^-), from agricultural uplands into coastal waters (cf. Groffman et al. 2003). Nitrate is a prime cause of eutrophication in coastal waters such as the Chesapeake Bay. Therefore, maintaining the ability of riparian zones to remove NO_3^- is a major component of efforts to control nitrogen (N) inputs to the Chesapeake Bay.

Riparian areas function as NO_3^- sinks when the dominant vector of water movement from uplands toward streams is shallow groundwater flow. These conditions create hydric or wetland soils in riparian zones, with high levels of organic matter and anaerobic conditions that foster denitrification of NO_3^- into N_2 gas, preventing its movement into streams (Hill 1996). As watersheds urbanize, hydrologic flow paths are altered, with large amounts of water moving as surface runoff or in infrastructure rather than as shallow groundwater (Schueler 1995), bypassing the riparian buffer zone. Moreover, alteration of flow paths, in combination with the fact that urban stream channels are often highly incised, results in drier riparian soils with lower rates of denitrification (Groffman et al. 2002, 2003). Drying of riparian soils actually fosters nitrification, an aerobic process that produces NO_3^- (figure 4). Thus, urban hydrologic changes may reduce this buffer function and can even convert riparian areas from sinks to sources of NO_3^- in urban and suburban watersheds.

Finding 5: Nitrate water pollution is higher in suburbs than in the city. Development on agricultural land alters hydrology and pollutant inputs as well as the social and regulatory

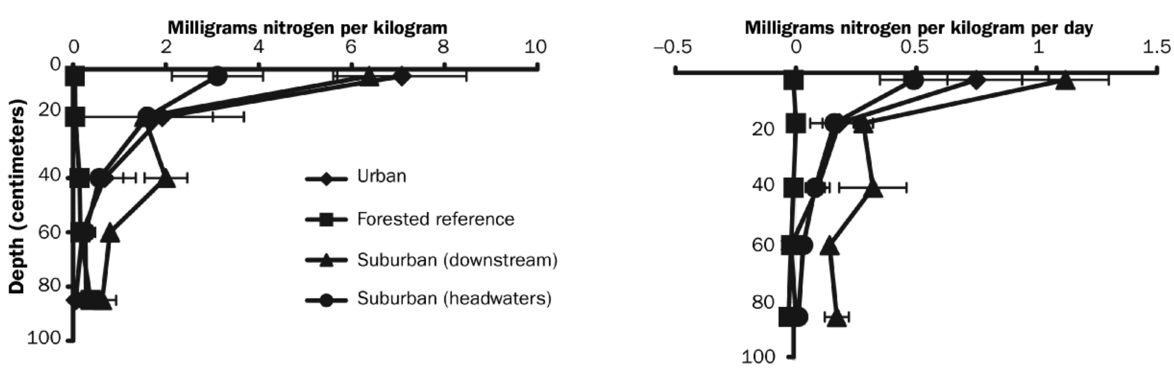

Figure 4. Soil nitrate (left) and potential net nitrification (right) at four riparian sites in Baltimore, Maryland. Values are the mean (± standard error) of two riparian transects at each site. Each transect consisted of two sampling locations five meters from the stream bank on opposite sides of the stream. Modified from Groffman and colleagues (2002).

framework for water quality. Research in the BES and elsewhere has demonstrated that N, a key nutrient affecting water quality, shows counterintuitive patterns. Nitrate levels in the Gwynns Falls stream are lower in dense urban areas than in either suburban or agricultural areas (figure 5; Groffman et al. 2004). This may be due to differential inputs. Nitrogen budgets estimate that inputs to urban areas, which are primarily from atmospheric deposition, are lower than inputs to suburban and agricultural areas, which include deposition but also fertilizer. Some city tributaries had very high levels of NO_3^-. Much of the N that we observed in urban streams appears to come from leaking sanitary sewers, a problem currently being addressed by Baltimore City. Suburban areas with septic systems had stream NO_3^- levels similar to those of agricultural areas, because septic systems discharge high amounts of NO_3^- by design (Groffman et al. 2004).

We have concentrated on N here, which is of regulatory concern, especially in the Chesapeake Bay region (Koroncai et al. 2003). Other aspects of stream quality, such as habitat for aquatic organisms or contamination by pathogenic microbes, road salt (Kaushal et al. 2005), and mercury, continue to be problems in the urban reaches of the Gwynns Falls watershed.

Finding 6: Land-use maps do not represent ecological heterogeneity effectively. Because land-use and land-cover changes are important results of urbanization, how these parameters are measured is important to both basic and applied science. The land-use and land-cover classifications frequently applied in urban areas were originally developed for coarse-scale, continent-wide use (e.g., Anderson et al. 1976). These classifications standardized the characterization of the landscape and were motivated by natural resource concerns. They have provided the basis for many additional classifications (e.g., Food and Agriculture Organization of the United Nations GeoNetwork; cf. Cadenasso et al. 2007).

Urban areas, however, are integrated systems consisting of built and biogeophysical components. Common classifications are inadequate to capture this coupled human-natural heterogeneity. For example, residential areas can be assigned high, medium, or low population densities, but this approach does not reveal the additional biophysical ways in which residential areas can differ from one another. Some neighborhoods have a continuous canopy of trees, others have trees only along streets, and still others lack trees. These areas are all recognized as being residential; however, variation in vegetation structure may have important implications for ecological functions such as nutrient cycling, energy use, and biodiversity (Cadenasso et al. 2006b). Social processes can also respond differentially to such vegetation contrasts.

A new classification has been developed that exposes the finer scale of heterogeneity in urban landscapes through increased categorical and spatial resolution (Cadenasso et al. 2007). The new system also discriminates patches that have both social and natural origins. Initial analyses of the landscapes in Baltimore show that the metropolis comprises a more complex, fine-scale array of patches than is usually resolved by the standard land-use classifications. Testing of structure-function relations using this new approach to urban structure is currently under way, and preliminary results suggest that this more accurate representation of landscape heterogeneity better explains relationships with water quality than previously available land-use classifications (Cadenasso et al. 2007).

Finding 7: Urban soils are not all disturbed. Urban soils are often assumed to be uniformly and drastically disturbed by humans (Craul 1992). Urban soils are considered to have massive structure; low available water and nutrients; high pH; low organic matter content; and contamination by heavy metals, salt, or other pollutants (Craul 1992). However, our work in the Baltimore and New York City metropolitan areas suggests that soils vary considerably in character over the urban landscape, making it difficult to define or describe a typical "urban soil" (Pouyat et al. 2003). Indeed, concentrations of calcium, potassium, magnesium, and phosphorus in Baltimore soils met or exceeded the recommended concentrations for horticultural soils. Although these data imply that urban soils have the potential to be highly productive for plants, other soil properties—such as high heavy-metal concentrations, bulk density, and droughtiness—and other features of urban environments suggest that plant productivity would be poor (Clemants and Handel 2006). In addition, other environmental factors, such as temperature or

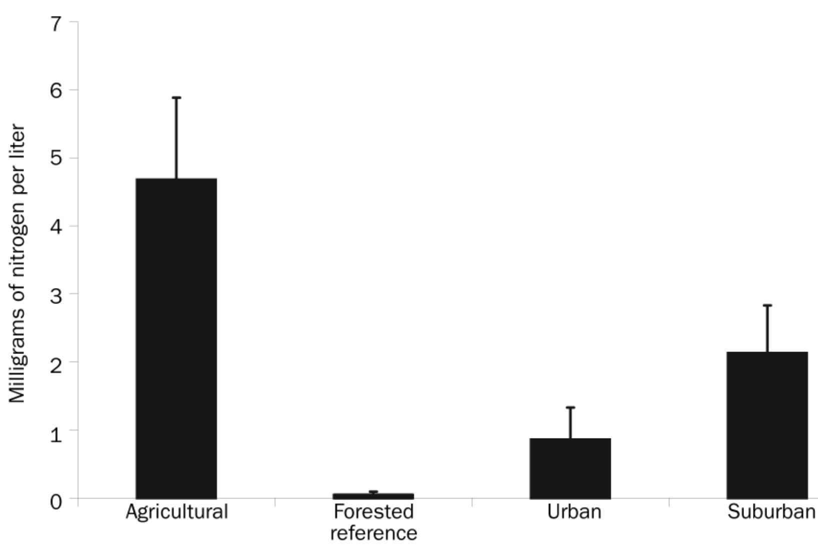

Figure 5. Mean (± standard error) nitrate concentrations in streams draining agricultural (McDonogh), forested (Pond Branch), urban (Dead Run), and suburban (Gwynns Falls at Glyndon) watersheds in Baltimore County, Maryland, sampled weekly from October 1998 through March 2006.

form of precipitation, can affect soil chemical and biological properties (Pouyat et al. 1995, Groffman et al. 2006).

Thus, not only human disturbance but also urban environment and management factors affect soil development. These factors result in a mosaic of soil patches that range from natural soil profiles that have been chemically altered, to partially disturbed profiles, to "made" soils and those that are paved over (Pouyat and Effland 1999). An understanding of the causes of these spatial patterns can lead to more effective soil surveys and to cost-effective landscape management and design.

Finding 8: Urban areas can contribute to carbon balance. How carbon (C) responds to the conversion of native ecosystems to agriculture, as well as to recovery from agricultural use, has been well studied. However, conversion to urban land uses has received little attention (Pouyat et al. 2006). Agricultural practices reduce soil organic C (SOC); however, after these practices have been abandoned, ecosystem development over decades usually leads to recovery of above- and belowground C pools in forested and grassland areas. By contrast, recovery of C pools from urban land-use conversions has been thought to be unlikely, or at least very slow, because of poor growing conditions (Craul 1992, Clemants and Handel 2006).

Soil organic C pools are affected directly through disturbance and management, or indirectly through urban environmental changes. The direction of the change, however, depends on the initial amount of SOC in the native soil (figure 6; Pouyat et al. 2003). Moreover, our analysis suggests that SOC storage in urban ecosystems is highly variable, with both high and low SOC densities present in the landscape (Pouyat et al. 2006). For those soils with low SOC densities, there is the potential to increase C sequestration in the absence of disturbance through supplemental watering or fertilization. For example, the soils of residential lawns appear to have the highest density of C in urban landscapes—higher than many forest soils in the conterminous United States (Pouyat et al. 2006).

Although managed turf-grass systems have the potential to accumulate SOC at relatively high rates, a complete budget of the C cycle relative to turf-grass maintenance must be completed to determine actual rates of C sequestration (Pouyat et al. 2006). Carbon emissions are associated with lawn mowing, irrigation, and the production and transporting of fertilizers (Pataki et al. 2006).

Vegetation C pools are also affected by urbanization, but the net gain or loss of aboveground C resulting from the conversion to urban land uses depends on the land use before conversion and the time since conversion. An inventory of nonforest land in the Baltimore area found that tree canopy cover and tree diameter varied inversely with the density of residential settlement (Riemann 2003). Residential land did not usually approach the vegetative biomass of forestland, but because of an increased density of woody plants and shrubs, it did contain more aboveground biomass per unit area than agricultural landscapes. Trees growing on residential land in the continental United States could sequester 20 to 40 teragrams C per year (Jenkins and Riemann 2003). This analysis does not consider lawn grasses or other vegetation in residential areas.

Integrative findings

We present four findings of relationships between biophysical and social patterns and processes. Although the previous eight findings had implications for the interaction of biophysical and social processes and patterns, the next four examples make these relationships explicit.

Finding 9: Vegetation change lags behind social change. An initial assumption in examining urban systems is that the ecological structure of particular neighborhoods reflects the existing social structure of those neighborhoods (Pickett et al. 2001). Our research indicates that this is not always true. For instance, the vegetative characteristics of Baltimore neighborhoods in 1990 are best explained by the social characteristics present 20 years earlier (figure 7). Such lags result from social and ecological change occurring at different rates (Grove 1996). For example, trees in the public right of way and on private property grow or senesce over long time periods compared with the time required for shifts in neighborhood population density, demography, or level of internal or external investment (Grove et al. 2006a, 2006b, Troy et al. 2007).

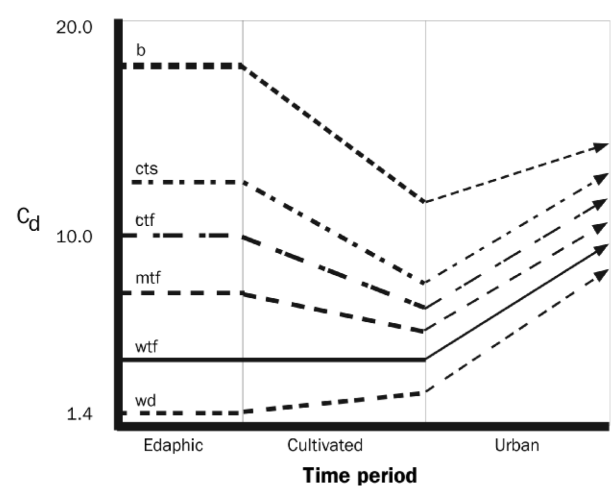

Figure 6. Proposed patterns of soil organic carbon density (C_d) through time as native soils are converted first to agriculture and then to urban cover. A range of native biomes is shown (b, boreal; cts, cool temperate steppe; ctf, cool tropical forest; mtf, moist tropical forest; wtf, warm temperate forest; wd, warm desert). Although the urban habitats in cooler climates may never reach the carbon sequestration potential of the native soils, our review of the literature suggests that with appropriate management, many urban soils can surpass native soils in carbon storage. Modified from Pouyat and colleagues (2006).

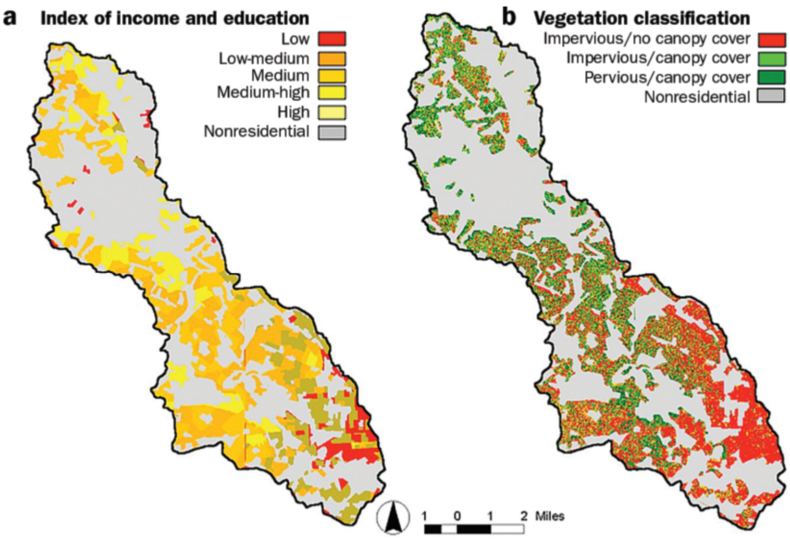

Figure 7. Maps of (a) residents' income and education and (b) vegetation cover, indicating a temporal lag between the two variables. Index of income and education is based on 1970 US Census block groups, and 1990 vegetation classification is derived from leaf-off (October 1990)/leaf-on (June 1991) Landsat Thematic Mapper imagery for the Gwynns Falls watershed, Baltimore, Maryland. Modified from Grove (1996).

Finding 10: Lawns can have beneficial social and biogeochemical functions in urban areas. Ecologists and environmentalists often perceive home lawns to be problematic. Residents' perceptions of the value of lawns, on the other hand, vary according to social and economic context. Field observations and interviews demonstrate that in underserved areas of the city, well-maintained lawns may contribute positively to neighborhood cohesiveness as symbols of homeowner investment (Grove et al. 2006a, 2006b), whereas in wealthier areas they are a source of contention concerning their aesthetic value and environmental effects (Osmond and Hardy 2004). The concern over environmental effects is reflected in the lower percentages of lawns fertilized in wealthy areas (56%) than in middle-class areas (68%; Law et al. 2004). In addition, the rate of fertilizer application is lower in the higher-income Baisman Run lawns than in those from the middle-class Glyndon catchment. Our results are consistent with those presented by Osmond and Hardy (2004).

Second, lawns have complex biophysical features. Lawns are highly managed, often intensively fertilized areas that are a concern as a source of nutrient pollution to ground- and surface water (Schueler 1995); however, they also have features that can increase N retention. For example, they have permanent cover and low soil disturbance, and they photosynthesize and take up water and nutrients for a much longer portion of the year than do forests or agricultural ecosystems. Data from the BES plots show that nitrate leaching and nitrous oxide flux from the soil to the atmosphere are not markedly higher in lawns than in forests. Perhaps even more interesting, variation among the lawns was not related to fertilizer input. Nutrient cycling in lawns is complex, and the effects of lawns on water quality are probably less negative than anticipated.

Golubiewski (2006) found marked stimulation of both C and N cycling in lawns relative to native shortgrass prairie in Colorado. Pouyat and colleagues (2006) showed that turfgrass can accumulate high densities of SOC, especially relative to arid grassland or scrub. Accumulation by turfgrass is equivalent to mesic grasslands and forests. Admittedly, turfgrasses require high resource inputs to survive in most areas of the United States, and those subsidies stimulate biogeochemical processes in arid environments and droughty periods in mesic climates. BES data and other recent studies suggest that lawns have higher biogeochemical and social value than we suspected: they can function as important N sinks and as an important catalyst for ecological and socioeconomic revitalization of underserved neighborhoods.

Finding 11: Urban ecosystems can retain limiting ecosystem nutrients. Urban areas are dominated by built structures and human activity, and it is easy to assume that natural processes are secondary (Macionis and Parrillo 2001). Ecologists expect human-dominated systems to have leaky biogeochemical cycles (Odum 1998). In one of our suburban watersheds, input-to-output budgets for N showed that inputs, in the form of atmospheric deposition and fertilizer, were much higher than streamwater outputs and that N retention was 75%, a level more similar to natural systems than we originally expected (table 1; Groffman et al. 2004). Similarly high N retention in urban watersheds was reported by Wollheim and colleagues (2005). This may be because a typical suburban ecosystem contains much young, actively growing vegetation that has a high capacity for N retention. We have also found that production and annual variation of inorganic N by mineralization is large relative to watershed-scale atmospheric deposition, fertilizer use, and food or sewage fluxes in watersheds (Groffman et al. 2004). The Baltimore ecosystem still leaks N, but it is not as leaky as we expected. Baltimore City and Baltimore County environmental managers have a long history of employing policy and best management practices in an attempt to reduce the N leakage to the Chesapeake Bay.

Total system C fluxes in Baltimore are expected to be dominated by fossil-fuel combustion. We established an eddy flux tower to measure total ecosystem carbon dioxide (CO_2) fluxes from an area dominated by single-family homes and mature trees. Eddy flux methods allowed us to determine whether the roughly 1-square-kilometer area surrounding the tower was absorbing or producing CO_2 (Grimmond et al. 2002). A human signal attributed to vehicle exhaust was apparent in higher CO_2 output on weekdays compared with weekends and holidays. However, natural processes of photosynthesis and respiration are significant in the C budget during the

Table 1. Inputs, outputs, and retention of nitrogen, in kilograms per hectare per year, for suburban, forested, and agricultural watersheds in the Baltimore metropolitan area.

	Suburban	Forested	Agriculture
Inputs			
Atmosphere[a]	11.2	11.2	11.2
Fertilizer[b]	14.4	0	60
Total	25.6	11.2	71.2
Outputs			
Streamflow[c]	6.5	0.52	16.4
Retention			
Mass	19.1	10.7	54.8
Percent	75	95	77

a. Mean deposition (wet plus dry) for 1998 and 1999, the latest data available for the CASTNET (Clear Air Status and Trends Network) site at Beltsville, Maryland.

b. For the suburban watershed, values are based on a home lawn survey (Law et al. 2004). For the agricultural watershed, values are estimated from Maryland Department of Agriculture recommended fertilizer rates for corn (120 kilograms of nitrogen per hectare per year in water year 2000) and estimated nitrogen fixation rates for soybeans (30 kilograms of nitrogen per hectare per year in water years 1999 and 2001).

c. Mean total nitrogen loads from 1999, 2000, and 2001.

Source: Groffman et al. (2004).

summer (cf. Coutts et al. 2007). The longer growing season and supplemental inputs of water and nutrients to urban vegetation may enhance the C uptake in urban areas compared with what may be expected. Thus, although this suburban area contains C sources that swamp the existing sinks, it may be possible to enhance the urban sink strengths through new policies. The fact that both N and C have large sinks in suburban areas is a tool that can be exploited for mitigating these pollutants.

Finding 12: Feedbacks through human health and policy connect urban social systems and urban environments. Traditionally, ecologists considered humans external "disturbers" of natural systems (McDonnell and Pickett 1993). Social science often supported this claim by arguing that urban landscapes are entirely products of human culture (Macionis and Parrillo 2001). As a result, the biogeophysical environment of cities receded in social and geographic scholarship. However, important feedbacks between social and biophysical factors have been found in Baltimore. For example, in 1880, 25% of children died before the age of one, primarily from waterborne gastrointestinal diseases. Infant deaths clustered in low-lying areas with inadequate drainage (Hinman 2002). The convergence of hydrology, human waste, disease dynamics, and the physical structure of the landscape resulted in regular outbreaks. In response, wealthier Baltimoreans fled upland, beginning a wave of suburbanization that continues.

Diseases associated with inadequate infrastructure forced a reorganization of the city government, including the appointment of a powerful health officer, who pushed the issue of sewers. By the time the sewers were completed in 1911, typhoid had been eliminated. Improvements in public health valorized land in low-lying areas, allowing for higher population densities in some neighborhoods and commercial conversion in others. The extension of sewers into annexed suburbs pulled greater numbers of white, middle-class people out of the city, leaving much of the old core for black Baltimoreans. Thus, feedback between environmental change and human change contributed to the transformation of Baltimore's social geography (Boone 2003).

Discussion

Although the initial application of ecological principles to urban areas dates from the early 20th century in the United States, during the last 40 years organismal perspectives (Stearns 1970) or coarse-scale budgetary approaches (Boyden et al. 1981) have been emphasized, neglecting many other ecological approaches in urban areas. Furthermore, the interaction of social and biogeophysical processes has received less attention than either disciplinary approach alone (Grimm et al. 2000). Therefore, the data on urban systems as spatially heterogeneous, dynamic, integrated social-ecological units remain limited (Pickett et al. 2001). The ecology of metropolitan systems is more complex and varied than it may at first blush appear, and with the expanding database, surprising results are appearing. What ecological theory can consolidate and advance this knowledge?

One source of theory is to expose the assumptions researchers make and to determine their applicability. Our 12 case studies can contribute to such an analysis. Correcting or expanding common assumptions in urban ecology can suggest a conceptual framework for urban ecological theory and point to topics requiring further work or integration into the larger structure. Of course, this is not the only approach to building theory, but it is one that can be supported by an empirical synthesis of the sort we present here. Synthesizing our results is a contribution toward a theoretical framework for urban ecology (box 1).

Social structure. Refining social assumptions suggests that different social and ethnic groups can have similar environmental perceptions and behaviors. Likewise, a given ethnic group or social class can exhibit internal differences with respect to environmental hazards experienced, environmentally effective actions, and environmental perceptions. In essence, although both are important drivers of social and biophysical processes, race and class can act separately.

Biodiversity. Urban biodiversity can often be high, and can include many native species. The distribution of species is heterogeneous and individualistic. Both exotic and native species have functional value in urban systems, and the interactions between the two groups require further work in the context of function.

Nutrient dynamics. For N and C, source and sink relationships may exhibit unexpected behaviors, and urban areas can con-

Box 1. Representation of Baltimore Ecosystem Study findings as hypotheses that may reveal gradients of response, structure, function, or model applicability.

Findings are grouped as primarily social, primarily biophysical, or integrative of the two. The last two columns contrast the assumed form and the nature of the finding from the Baltimore Ecosystem Study (BES). The assumed form can be considered a limited view of the hypothesis, and the findings from the BES represent an expanded or alternative view. The gradient between the assumed and actual finding represents the range of possibilities that may exist across metropolitan systems, and hence is a tentative framework that may guide future comparisons.

Category	Assumption	Finding from BES
Social		
Social status and environmental concern	Different across groups	Similar across groups
Environmental inequity	Affects minority groups	Affects all economically disadvantaged groups
Biophysical		
Biodiversity	Low in city	High in city, with valuable elements
Riparian function	Sink function in urban environments	No sink function, or acts as source
Stream nitrogen loading (spatial distribution)	Lower in suburbs than in city	Lower in city than in suburbs
Representing urban heterogeneity	Standard methods adequate	Requires new classification system
Urban soil heterogeneity	Uniformly artificial or disturbed	Mosaic with some unmodified or little-modified profiles
Carbon sequestration	Source only	Some sink functions exist
Integrative		
Social-biophysical linkages	Instantaneous	Lagged
Lawns and biogeochemistry	Only nutrient sources; only socially contentious	Nutrient sink; social value
Urban ecosystem retention	Only anthropogenic control	Both anthropogenic and natural controls
Social-biophysical feedbacks	Minor	Pronounced

tribute to the retention of polluting forms of these elements. Understanding the dynamics of N in particular goes beyond evaluating human density and impervious surface as drivers, and requires disentangling the roles of different kinds of water and wastewater infrastructure and their interactions. How different kinds of households manage the environment plays a role in these dynamics. Lawns, as a persistent, subsidized, and widespread component of urban systems, can play a role in the nutrient retention achieved by urban ecosystems.

Heterogeneity. The notable spatial heterogeneity of urban systems is not well documented by standard land-use models. Alternative, integrative models are appropriate. Soils, like the aboveground structure of urban systems, are highly heterogeneous, and contain native or remnant patches, made patches, and paved patches. The interaction of various kinds of heterogeneity in urban systems is a major open question.

Natural-human coupling. Lags exist in the control of biophysical structure by social patterns and processes. Both anthropogenic and natural components of cities and suburbs contribute to the control of ecosystem dynamics; control is not only by the anthropogenic component. Finally, couplings between social processes and environmental structure and processes have been demonstrated to shape the urban ecosystem.

Our results, along with those of other urban ecological studies, suggest an initial framework for a theory of urban ecosystems. That theory does not see control of the urban realm as a purely social phenomenon, or as one that is uniform across space within a metropolis or between cities. It suggests that urban ecosystems are complex, dynamic biological-physical-social entities, in which spatial heterogeneity and spatially localized feedbacks play a large role (Cadenasso et al. 2006a). This conception goes well beyond the early- and mid-20th-century view of cities as input-output devices driven only by human design and decisions.

It may be valuable to consider our results as a step toward a framework for comparison of different cities. That the assumptions that we and other scholars held failed in Baltimore suggests that these assumptions identify useful gradients along which metropolitan areas may differ (box 1). Viewing them as gradients can encourage analyses of the assumptions about social processes, biogeophysical fluxes, and the relationships between the two, in a wide array of cities.

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