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# Advancing urban ecological studies: Frameworks, concepts, and results from the Baltimore Ecosystem Study

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**Abstract** Urban ecological studies have had a long history, but they have not been a component of mainstream ecology until recently. The growing interest of ecologists in urban systems provides an opportunity to articulate integrative frameworks, and identify research tools and approaches that can help achieve a broader ecological understanding of urban systems. Based on our experience in the Baltimore Ecosystem Study (BES), Long-term Ecological Research project, located in metropolitan Baltimore, Maryland, USA, we identify several frameworks that may be useful in comparative urban studies, and may be worthy of consideration in other integrative urban ecosystem studies: (i) spatial patch dynamics of biophysical and social factors; (ii) the watershed as an integrative tool; and (iii) the human ecosystem framework. These frameworks build on empirical research investigating urban biota, nutrient and energy budgets, ecological footprints of cities, as well as biotic classifications aimed at urban planning. These frameworks bring together perspectives, measurements, and models from biophysical and social sciences. We illustrate their application in the BES, which is designed to investigate (i) the structure and change of the urban ecosystem; (ii) the fluxes of matter, energy, capital, and population in the metropolis; and (iii) how ecological information affects the quality of the local and regional environments. Exemplary results concerning urban stream nutrient flux, the ability of riparian zones to process nitrate pollution, and the lags in the relationships between vegetation structure and socio-economic factors in specific neighbourhoods are presented. The current advances in urban ecological studies have profited greatly from the variety of integrative frameworks and tools that have been tested and applied in urban areas over the last decade. The field is poised to make significant progress as a result of ongoing conceptual and empirical consolidation.

**Key words:** city, ecosystem, framework, interdisciplinary, patch dynamics, social factors, urban, wakershed.

## INTRODUCTION

Most American ecologists have been strangers to urban systems. The vast majority of ecological attention has been devoted to systems that are considered to be wild, rural, or only modestly and transiently affected by humans. This urban ecological vacuum has been countered by the work of a few pioneering ecologists and other biologists. However, the primary locus of research and scholarship on urban systems has been in social sciences, geography, economics, and urban planning.

Over the past 15 years, mainstream ecology in the USA has awakened to its neglect of settlements and urban systems (McDonnell & Pickett 1993). Consequently, an increasing number of ecologists has begun to add to the body of knowledge about urban areas. However, it is still fair to say that urban systems are an open frontier for ecologists, even if this frontier is well marked with the signs of other disciplines.

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This paper gives an overview of the Baltimore Ecosystem Study (BES), Long-term Ecological Research (LTER) project. This study is one of two urban research programs funded by the US National Science Foundation (NSF) as part of its 26 site LTER Network. Long-term ecological studies have been a strategic funding focus of the NSF since 1980, to mitigate for the fact that most ecological research to that point had been short-term, in spite of the longevity and slow rates of many ecological processes (Likens 1989). Ecosystem succession, response to disturbance, and soil development are notoriously slow processes, which are either poorly documented or predicted from studies of short duration. The LTER sites have produced important data and models concerning many different ecological systems and the Network facilitates cross system comparisons. The prospect of long-term funding may well help cement the ecological presence on urban frontiers. We present this overview of BES as a point of reference for other ecologists embarking on or consolidating urban research, in hopes of stimulating comparison and collaboration.

## URBAN ECOLOGICAL SYSTEMS

The term urban is both familiar and difficult. Although most governments have specific and complex definitions of urban, these are insufficient to define systems in a way suitable for ecological research. For example, the US Census Bureau defines urban in terms of four criteria: 1) human population density, 2) legal municipal boundaries, 3) colocation with built-up areas, and 4) daily commuting radius. Some States, such as those in New England, and the State of New Jersey, define municipalities in ways that differ from the remaining 43 States. If ecologists were to adopt these definitions for all their studies, many important influences and contexts would be missed in urban studies. Hence, it is important to specify in a given ecological study what is meant by urban (Theobald 2004). McIntyre *et al.* (2000) suggest that recognizing urban systems as heterogeneous mosaics is key to establishing the ecological definition to be used in a particular study. Such complex habitats can be ordinated along conceptual gradients (McDonnell & Pickett 1990), or in some cases, can be usefully studied as linear transects beginning in dense urban cores and ending in wild or rural lands. The use of specified gradients is a plausible solution to the problem of multiple legitimate concepts of urbanization (McIntyre *et al.* 2000; Theobald 2004).

These complexities show that the term urban is a flexible one, which must be defined explicitly in a given study. Such definition may be quantitative or qualitative, or it may be multidimensional or based on a single parameter. In BES, urban is used in the broad sense to refer to the entire metropolitan area, which covers five adjacent counties as well as Baltimore City. In the narrow sense, BES researchers use urban to refer to study sites or their surroundings located in the densest, most intensely settled core of the metropolis. In this narrow sense, urban contrasts with other categories such as suburban, exurban, or hinterland.

## A HUMAN ECOSYSTEM

Ecologists are quite comfortable studying complex systems, comprising biotic and abiotic components, which are linked by flows of matter, energy, and information. This basic concept is as applicable to urban settlements as it is to areas in remote wilderness or uninhabited locations (Odum 1997). It is clear, however, that the biotic component of urban ecosystems needs to be fleshed out in particular ways. Such an expanded view of ecosystems becomes part of the connotation of urban ecological studies. We will say more about a specific framework later. Now it is sufficient to note that urban, and indeed all ecosystems inhabited by humans, must be modelled to include the human individuals as well as the social aggregations they generate or influence. It is not sufficient to include humans only as demographic entities, characterized by density, birth, death, and migration. Humans must also be represented by the institutions that organize and affect daily life, by the cultural and social resources they and those institutions rely on, and by the temporal dynamics exemplified by individuals, families, organizations, neighbourhoods, economies, etc. (Machlis *et al.* 1997). Social scientists and geographers have compellingly documented the spatial complexity, and flows of population, information, capital, and influence, which must be important drivers of urban ecological processes (Logan & Molotch 1987; Gottdiener & Hutchison 2000). It is perfectly reasonable to incorporate such factors and processes into ecosystem models. Indeed, Tansley (1935) in defining the ecosystem concept, was anxious to have ecologists address the role of people in ecosystems. Similarly, Odum (1997) exhorted ecologists to include humans in ecosystems. In spite of the fact that Odum's ecosystem modelling strategy shaped ecosystem ecology for decades, ecologists did not, in general, heed his advice to include humans. Clearly, however, the ecosystem concept is fully capable of accounting for humans. Such an expanded view of ecosystems is associated with urban ecological studies. Again, we will say more later about a specific framework for incorporating humans into urban ecological studies.

## APPROACHES TO URBAN ECOSYSTEMS

We have noted that mainstream ecology is a late migrant from country to city.[a] Other disciplines, or pioneering biologists, have been here before. What did they accomplish, and how does that work shape, motivate and differ from current work?

Botanists, zoologists, and wildlife biologists, some with ecological credentials, have explored the biota of cities for a long time. Most work known to us dates from after World War II, when the devastation of cities in Europe and Japan suggested cataloguing their biotic resources, and stimulated understanding of succession on vacant parcels (Sukopp *et al.* 1995). From this foundation, a firm knowledge of urban floras has emerged in many parts of the world (Schmid 1975; Clements 1983; Mucina 1990; Zimny 1990; Kent *et al.* 1999). Botanists have identified a suite of plant species that specialize on urban habitats, as well as many native and exotic species that are predominant volunteers in city habitats (Rapoport 1993). Biotic richness is often quite high in cities, as it reflects a

[a]We use the term 'city' here as a shorthand for the entire range of urban environments.

roster of both native and introduced species (Pickett *et al.* 2001). While some city habitats, especially inaccessible or isolated remnants that escaped development or cultivation, support rare or endangered species, ecologists generalize that the floras and faunas of cities tend to be dominated by habitat generalists, early successional trees and herbs, and species that can tolerate disturbance. An important open research question is the functional role of species in the ecological processes of urban habitats, regardless of their status as native vs. introduced.

Aggregating species into community types is another long-standing interest of urban researchers. In order to understand the biotic resources of cities, ecologists have mapped the community or biological habitat types available. Most often labelled 'biotope mapping', this approach has flourished in Europe, but has also found application elsewhere (Sukopp & Weiler 1988; Frey 1998; Werner 1999). It has helped identify sites that can support urban wildlife, or which can provide amenities to residents, or promote plant conservation in the city.

Another approach to urban research, which is a subset of ecosystem ecology, has been a 'metabolic' or budgetary one. The concern here is with the inputs and outputs of energy and matter. An early example in this vein was done in Hong Kong (Boyden *et al.* 1981; Warren-Rhodes & Koenig 2001). These studies have documented the heterotrophic nature of cities, the large amounts of waste heat and matter that cities produce. The budgetary approach has awakened in many people the desire to make cities more energy efficient, more retentive of storm water, and more capable of producing at least some of the food resource its residents require (Wackernagel & Rees 1996). Wastage of foodstuffs, such as milk, has been identified as an important part of the nitrogen budget of cities, and hence provides an opportunity to reduce the nitrogen pollution of 'downstream' ecosystems by cities (Grimm *et al.* 2003).

Closely related to the concern with energy and material budgets of cities, is the focus on ecological footprints (Rees 2000). This kind of model summarizes the resource requirements, and the needs for waste disposal and processing in terms of land area. Figures estimated for various cities show supporting land areas are often two orders of magnitude greater than the size of the municipality itself. The ecological footprint is chiefly a metaphor for the resource and waste processing requirements of urbanized areas. It is not strictly a model of the connections to specific places that any given city relies on or exploits. Such complex and focused networks cannot be represented by a blanket area estimate. Some ecologists have introduced a degree of spatial reality to footprint analysis by indicating at least some of the specific areas a particular city is linked to (Luck *et al.*, 2001).

Hydrologists have been quite active in cities. They have modelled the contributions of various land cover types to the flow of water from cities. They have also documented reduced infiltration and lowered ground water tables. Current work in urban hydrology is aimed at increasing understanding of the complex flow paths that water encounters in urban systems (Brun & Band 2000). This work is built on similar improvements in non-urban hydrological models. Underlying the approach is a variable source area concept (Black 1991; Pitt 1995; Voinov *et al.* 1999; Pauleit & Duhme 2000), which suggests that water output is determined by the combination of spatial areas that have different capacities to absorb or to shed water. The hydrological concept of variable source area (VSA) is parallel with the ecological concept of patch dynamics (Wu and Loucks 1995, Pickett *et al.* 1997).

Social scientists have also claimed an ecological approach. The earliest expression of this is seen in the work of the Chicago School, established at the University of Chicago in the early 20th century (Burgess 1925). Social science was consolidating as a discipline at that time, and Burgess and Park adopted analogies from ecology as their theoretical basis (Melosi 2003). Burgess and Park used competition as the driving mechanism for distribution of different social and economic groups in the city. They furthermore described city dynamics in terms of ecological succession, assuming the deterministic and end-point orientated view of the time. This model has been criticized for a long time, especially by social scientists wishing to employ individual behaviour rather than group-based ecological processes as mechanisms. Recent syntheses that highlight spatial structure and dynamics of the city critique the ecological basis of the Chicago School (Gottdiener & Hutchison 2000), apparently not realizing that the simple-minded competition theory and deterministic succession to climax, upon which the Chicago School were founded, were long ago replaced in ecology. Indeed, the replacement of the Chicago School by the socio-spatial approach is parallel to the patch dynamics approach of ecology (Pickett and White, 1985), of which Gottdiener and Hutchinson (2000) were apparently unaware. Still, the classical social ecology approach has spawned many important lines of inquiry. These include political economy, social ecology of place, and political ecology (Logan & Molotch 1987; Bryant 1992; Dow 2000). Contemporary social ecologists define the field as a biological science that addresses how humans organize themselves to exploit and allocate recources (Grove & Burch 1997). These social science specialties have been brought together in the socio-spatial approach by Gottdiener and Hutchinson (2000).

Urban ecology is also used as an approach in urban planning, especially in Europe. Carried out in city and regional agencies, the approach combines biological information with planning methodologies (Schaaf *et al.* 1995; Flores *et al.* 1997; Thompson & Steiner 1997; Pickett *et al.* 2004). The goals are often to identify or design open spaces that provide a contrast from the noise and hard surfaces of cities, conservation, microclimatic, or other amenities in cities. Traffic calming, storm water management, and noise reduction are other goals aimed to protect pedestrians, reduce aggressive behavior, provide a pleasant environment for local residents, and protect the downstream environment. It is not surprising that other disciplines, such as planning, social science, and economics adopted what seemed to them to be reasonable ecological perspectives, given the relative neglect by mainstream ecology of the localities about which those disciplines needed data.

Now that ecologists themselves are attempting to develop and use frameworks for the study of urban systems, approaches that are familiar to ecologists are being adopted and applied (Zipperer *et al.* 2000). We give overviews of three frameworks that seem to us to be especially useful.

Patch dynamics is the first of these. Patch dynamics recognizes that spatial heterogeneity is a key attribute of ecological systems. Emerging in the late 1970s, and originating from much the same impetus as the spatially focused discipline of landscape ecology, patch dynamics describes the spatial structure of areas, the flows of materials, energy, and information across spatial mosaics, and the changes in individual spatial components of the mosaic as well as in the mosaic as a whole (Pickett *et al.* 2000). In other words, patch dynamics is concerned with the spatial structure, function, and change of mosaic systems. It is important to note that the mosaics can comprise discrete, bounded patches, or can be conceived of as gradients or fields defining continuous surfaces of differentiation. Patch dynamics is equally applicable to biotic or physical spatial structure so familiar to ecologists, and to social patchiness (Field *et al.* 2003). Earlier, we noted that patch dynamics parallels the variable source area approach from hydrology, and the socio-spatial approach from social science. We will describe this approach further using examples from BES.

Adapting the ecosystem concept to urban systems has, as already mentioned, required inclusion of human and social components. The tool we have found most useful for accomplishing this addition is the Human Ecosystem Framework. Originally proposed by social ecologists Bill Burch, Gary Machlis and colleagues (Machlis *et al.* 1997), the framework describes the various structures and kinds of interactions that modelling humans as components of ecosystems would require. The framework identifies the resource base of the ecosystem, which includes biophysical and social resources (Fig. 1). We recognize that the human ecosystem has spatially explicit structure, and this insight is included in the framework as well (Pickett *et al.* 1997). The framework also lays out the kinds of ways in which people organize themselves to exploit and manage those resources, and to accomplish the various functions of life. The framework finally recognizes that the individuals and institutions change over time, based on inherent human physiological rhythms, and institutional 'life cycles' (Fig. 1). The Human Ecosystem Framework contains the menu that will be selected from to construct specific models of ecosystem function. The framework is not itself a model.

The third approach is one that recognizes urban ecosystem as regions. This approach is emerging at the boundary between planning and ecology (Forman 2004). Having deep roots in the work of Patrick Geddes, and hence connections to social sciences and geography (Welter 2002), the approach is compatible with both patch dynamics and the Human Ecosystem Framework. Urban regionalism emphasizes that city dwellers must have access to and responsibility for the distributed resources and amenities upon which they depend. Watersheds, floodplains, large natural areas, connecting corridors, green buffers, green water management infrastructure, and recreational parks and playgrounds are all part of the kinds of patches that must be planned for, appropriately arranged, and phased in as urban regions grow and change. The incredible rate of urban expansion in post-industrial, newly industrial, and even agriculturally based societies makes this approach an important one. It is also one that is hungry for the kinds of ecological data that can be supported by all the other approaches we have reviewed here. Although general principles can be drawn from existing work, each urban region may require specific data derived locally to make the best informed decisions about what sorts of biotic, built, social, and hybrid patches it requires and how they might appropriately be arranged. Notably, this work linking design and ecology explicitly incorporates values of the patrons of the plan, affected communities, and designers. This approach builds on science, but it goes beyond science.

## THE BALTIMORE ECOSYSTEM STUDY

Baltimore, Maryland, is a metropolitan area comprising the City of Baltimore and five surrounding counties. Nearly 3 million people live in the metropolitan area. Three streams drain the city and much of adjacent Baltimore County, and these watersheds serve as important substrates for our ecologically based studies. An additional watershed, located in Baltimore County, serves as a forested reference with which to compare the urban and urbanizing watersheds. The

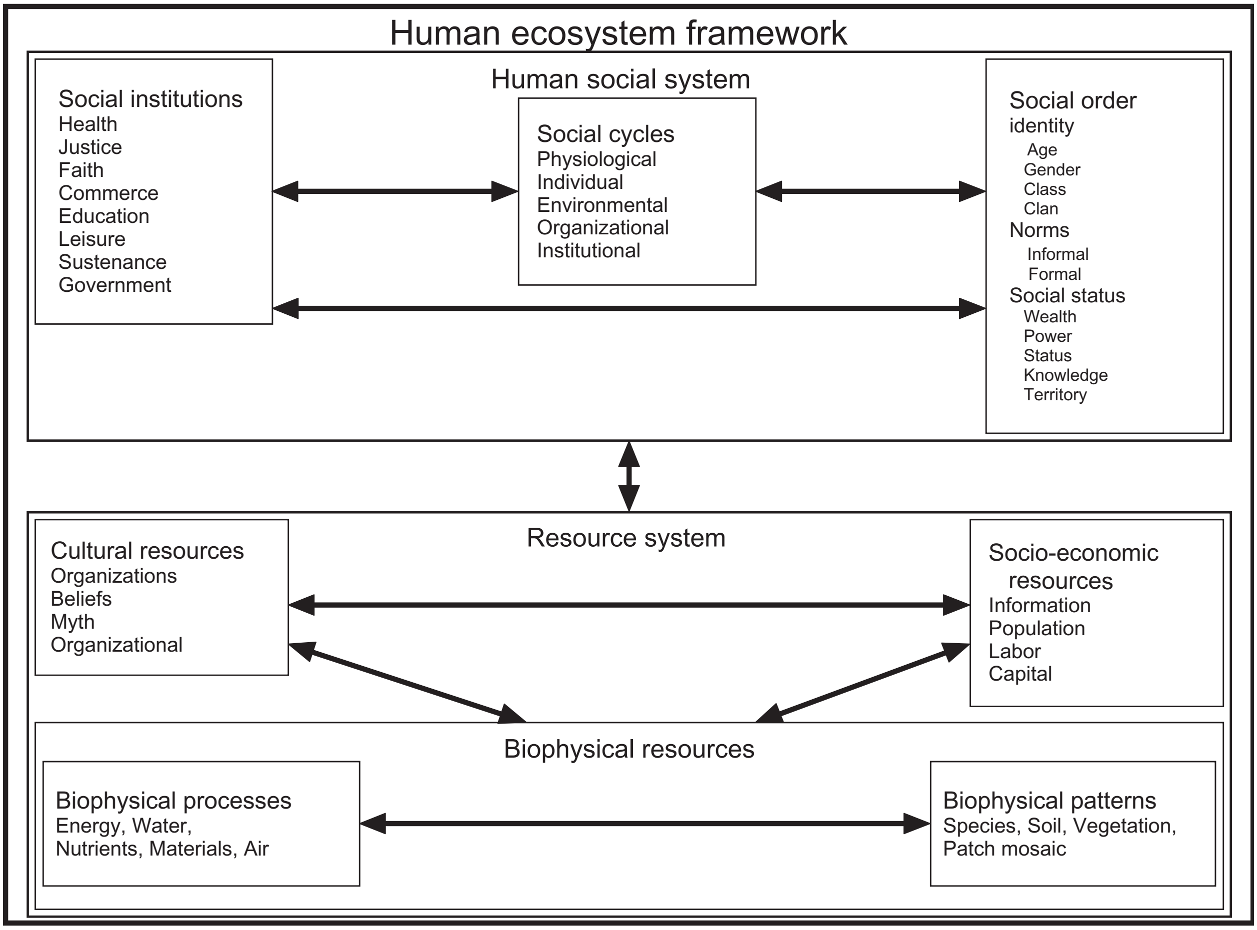


**Fig. 1.** The Human Ecosystem Framework, which includes a complete roster of the structural and functional variables that can motivate hypotheses and inform models addressing inhabited or managed ecosystems. Modifed from Machlis *et al*. (1997).

physical and biotic characteristics of the region are described more fully on the BES web site (http://www.beslter.org/frame2-page_1_4.html). The climate is humid subcontinental, with warm summers and mild winters. Rainfall amounts to 1090 mm per year, and is roughly evenly distributed over the year. The metropolitan area is located primarily on the Piedmont physiographic province, with portions on the Coastal Plain province. The original forest in the region was dominated by chestnut oak (*Quercus prinus*) and American chestnut (*Castanea dentata*) prior to its demise due to the chestnut blight, and tulip poplar (*Liriodendron tulipifera*), with a variety of other hardwood species as associates.

The BES project consists of three components: (i) integrated human ecosystem research, relying on input and interaction among biological, physical and social scientists; (ii) education, pursuing an inquiry based philosophy, and interacting with elementary, secondary, and college audiences, in addition to graduate training, and teacher workshops; and (iii) engagement with local communities and governmental agencies. Integrated scientific research is of course our core activity. The remaining activities serve this central goal, or serve the communities in which we work. We conduct education in order to share our results and expertise with students and teachers, and to assist in curriculum focused on urban systems (Berkowitz *et al*. 2003). Community engagement permits us to know the needs and interests of local residents, managers, and decision leaders as we plan our research. It also helps communicate our results and ecological insights to audiences who have an interest in learning and applying ecological information. Community engagement also builds the goodwill necessary for us to be able to work on private properties, the commons, and agency holdings and operational territories. The success of the project requires all three of these seemingly disparate components – science, education, and engagement. This strategy requires close interaction between members of BES who are scientists, managers, educators, and community facilitators.

The principal participants in BES come from 34 different institutions, ranging from research universities, teaching colleges, private research institutions, federal agencies, public and private schools, not-for-profit community action organizations, and community associations. The project hosts quarterly meetings to discuss new and existing research and application, an annual technical scientific meeting, and an annual community open house. BES researchers are members of two important committees that facilitate exchange between research, agency, and community leaders: the Revitalizing Baltimore Technical Committee, and the Watershed Linkages Committee. The important community engagement function is spearheaded by the Parks & People Foundation (http://www.parksandpeople.org).

## RESEARCH QUESTIONS FOR BALTIMORE

Baltimore Ecosystem Study research is driven by three general questions. Each researcher or interdisciplinary research team must of course ask much more specific questions than these in order to conduct well-justified, focused research based on clearly articulated hypotheses. However, these general questions are a common touchstone for all projects that contribute to BES research, and they are helpful in communicating general project goals to people outside the project. The three questions are:

1. How do the spatial structures of socio-economic, 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, matter, 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 two questions address the structure and function of urban systems from an integrated multi-disciplinary perspective. The third question assesses how people understand and use the information in their decisions. Before presenting some illustrative – and in some cases surprising – results from these questions, we will identify key tools used to integrate this diverse group of researchers addressing a complex system.

## INTEGRATIVE CONCEPTUAL TOOLS

BES uses several conceptual tools to provide centripetal force for the project: (i) the Human Ecosystem Framework; (ii) watersheds; (iii) patch dynamics; (iv) comparative studies; (v) long-term data; (vi) simulation modelling; and (vii) participatory action research. We have introduced several of these tools in our overview of approaches used in urban ecological research. Here we indicate how those tools plus the additional ones just listed, are used to integrate BES.

### Human ecosystem framework

The Human Ecosystem Framework (HEF) is crucially important for reminding all participants that they are studying, explaining, or contributing to management of a complex, inhabited ecosystem (Machlis *et al.* 1994, 1997). In particular, it reminds groups of investigators of the parameters they must consider when building joint models. This has been especially important in linking biophysical scientists with social ecologists and political ecologists (Grove & Burch 1997; Grove *et al*. 2005, Pickett *et al*. 2005). For example, ongoing research is examining how social status, which is one of the parameters identified by the HEF, functions as a driver of ecological processes and structures in the metropolis. Social status as represented by different marketing groups, or clusters of similar lifestyle and purchasing patterns affects vegetation status throughout the metropolis. A commercially available market segmentation database, called PRIZM (Claritas 1999) provides a basis for assessing lifestyle groupings. This research question has promoted a new theoretical construct, the 'ecology of prestige' (Grove *et al*. 2006), which posits that environmentally relevant household behaviours are driven by desire to express membership in different social groups, rather than by simpler measures of income or education. Note that this shift from sole reliance on indices of demographics, wealth, education, and ethnicity, which dominated explanations of industrial era urban dynamics, to a consumption based social theory, reflects a shift to a post-industrial economy and mode of urban organization (Grove *et al*. 2006).

### Watersheds

Watersheds are another powerful integrative tool for BES (Band & Moore 1995; Law *et al*. 2004). The directional flow of water, along with its ability to transport resources and pollutants, are two key integrative functions of watersheds. Although differences in below ground flow and overland flow may complicate the use of watersheds in some cases, they remain a compelling tool. Hydrologists, as already noted, recognize the variable source area approach as a way to understand watershed function (Black 1991). By dividing watersheds into areas that differ in their ability to absorb or yield water, a more mechanistic understanding of the water yield from a watershed can be achieved. One of the powers of the watershed approach is that large catchments can be divided into smaller catchments, or aggregated into still larger drainages. In other words, the source areas can be subdivided or grouped together. Therefore, the watershed approach can be scaled to match the extent or grain of the research question, or of the model or theory used to link with another discipline. This approach resonates with the hierarchical patch dynamics approach (Wu & Loucks 1995) discussed below.

BES concentrates on six watersheds for different purposes. Gwynns Falls is the largest of our intensively sampled watersheds, covering 17 150 ha. Gwynns Falls is sampled by three stations on the main stem of the stream, focusing on headwaters, middle and upper reaches, and the downstream reach. The sampling stations represent a gradient of urbanization, and the downstream reach represents the net output of the watershed. The contribution of the upper reaches can be assessed by subtraction. In addition, four tributary subwatersheds of Gwynns Falls, representing contrasting land covers are sampled. The tributary watersheds represent (i) dense urban, with industrial and commercial as well as residential land; (ii) early 20th century rowhouse suburbs; (iii) agricultural land in a suburban matrix; and (iv) recent low density suburban development. All Gwynns Falls stations are sampled weekly for water flow and quality. Pond Branch, a tributary of the Baisman Run, serves as the forested reference watershed for comparison to the more built-up watersheds. This gauged catchment has been sampled weekly for flow and water chemistry. Smaller watersheds were added to the sampling network to address specific situations of land cover and management. The remainder of Baisman Run represents recent large-lot, suburban development. Moore's Run is the location of the atmospheric eddy flux tower, and drains heavily wooded older suburbs. Mine Bank Run is the site of a restoration project conducted by Baltimore County, in which BES scientists measure variables that can assess the success of the restoration. The Minebank Run project seeks to restore stream channel geomorphology, riparian function, and in-stream nutrient and organic matter retention. Finally, a 367-ha storm drain catchment, Watershed 263, in Baltimore City has recently been added to the network. Sampling is conducted in the storm drain pipes in two subwatersheds on the same schedule as the major surface drainages. Watershed 263 is an urban restoration and greening project to test the impact of extensive tree planting and removal of impervious surfaces on storm water quality.

**Patch dynamics**

Patch dynamics is another of the integrative tools in BES. This concept, introduced earlier, focuses on spatially explicit structure of ecological systems, and the functional and dynamic properties of spatial mosaics. This concept has been important in mainstream ecology as a way to address and evaluate the role of spatial heterogeneity in a wide variety of systems (Pickett & White 1985; Pickett & Rogers 1997; Pickett *et al.* 1999). We hypothesized that it would be important in urban systems as well, because they are notoriously patchy (Fig. 2). Urbanists have commented on this patchy nature extensively (Jacobs 1961; Clay 1973).

Biophysical patches are a conspicuous layer of heterogeneity in cities. The basic topography, although sometimes highly modified, continues to govern important processes in the city. The watershed approach has highlighted the importance of slopes, and of patchiness along slopes, in water flow and quality. Steep areas are often the sites of remnant or successional forest and grassland in and around cities. Soil and drainage differ with the underlying topography. Vegetation, both volunteer and planted, is an important aspect of biophysical patchiness. The contrast in microclimate between leafy, green neighbourhoods *vs.* those lacking a tree canopy is a striking example of biotic heterogeneity (Nowak 1994). Additional functions may be influenced by such patchiness, including carbon storage (Jenkins & Riemann 2003), animal biodiversity (Adams 1994; Platt *et al.* 1994), social cohesion, and domestic violence (Dow 2000).

Patchiness is not restricted to biological and physical properties of the metropolis. Indeed, social and economic differences are spatially pronounced in and around cities. Patchiness can exist in such social phenomena as family structure and size, age distribution of the human population, wealth, educational level, social status, consumer preferences, and environmentally relevant behaviours (Burch & DeLuca 1984; Field *et al.* 2003). The ecology of prestige, introduced earlier (Grove *et al.* 2006), is an example of a theoretical structure that is best expressed in a spatially explicit framework, such as patch dynamics. Because none of these social patterns are fixed in time, the dynamic aspect is as important as the spatial aspect. This insight is a key feature of the socio-spatial approach (Gottdiener and Hutchinson 2000).

Because urban areas are coupled human-biophysical systems, it is important to exercise patch dynamics on combined or hybrid patches, not simply on biophysical or social patches separately. For example, in BES a patch mosaic is being constructed using a field survey that combines physical characteristics

**Fig. 2.** False colour infrared aerial photography of the Rognel Heights neighbourhood, and the adjacent Edmonson Avenue commercial district, obtained in October 1999, before leaf drop. The patches outlined on the image differ in kinds and density of built structures and vegetation. Photo courtesy Baltimore Ecosystem Study Long-term Ecological Research.

of the buildings present, aspects of the vegetation, indices of social cohesion, and evidence of specific human behaviours (e.g. litter, lawn furniture, play equipment, graffiti).

A final kind of patch dynamics appears when ecological concerns are combined with those from urban design. Most people, and indeed most architects and designers, assume that the built environment is a permanent fixture. However, buildings and infrastructure change, as does their built and biophysical context. This sort of elasticity in the urban system suggests a powerful way to reconceptualize urban design as an adaptive, contextualized pursuit (Pickett *et al.* 2004). Such dynamism combines with the growing recognition of the role of urban design in improving the ecological efficiencies and processes in cities. Although this application of patch dynamics is quite new, it has great promise to promote the interdisciplinary melding of ecology and design, and to generate novel designs with enhanced environmental benefit (McGrath *et al.* 2006).

**Additional integrative tools**

We will only briefly mention some of the remaining tools for integration, with a short example of each. Comparison brings our project together. BES research is exploring faunistic similarities and differences with Budapest, Hungary, and nitrogen dynamics with Paris, France. Long-term data are a focal point for interdisciplinary work. For example, the permanent forest sampling plots have brought together biogeochemists with zoologists and botanists. Social scientists have explored structural contrasts between neighbourhoods surrounding the different long-term stream sampling stations. Finally, simulation modelling has brought social scientists, economists, and hydrologists together.

## EXAMPLES OF RESULTS FROM INTEGRATED URBAN ECOLOGICAL STUDIES

We will give three examples of integrated research that uses several of the tools and frameworks discussed above. We emphasize examples that have practical importance in our region, or which seek to link patterns and processes across disciplines. We cast the results in terms of the surprises they revealed to us.

Urban areas are usually considered to be so thoroughly dominated by the built and human, that ecological processes are assumed to be overwhelmed by human alterations. The stream sampling mentioned above, coupled with estimates of other components of the ecosystem nitrogen budget allowed us to test this assumption. Atmospheric N input is constant across the Mid Atlantic region in which Baltimore is located, so that forms a baseline for all our sites. Fertilizer input is derived from Maryland Department of Environment recommendations, and the absence of fertilization in native forest. Stream outputs are from the weekly sampling described earlier.

The amount of N retained on an annual basis is, as expected, greater in the forested watershed (94% on a mass basis). Agriculture retains 85% of N applied to that land cover type, while suburban watersheds retain 71% of N inputs. The suburban retention rate is surprisingly high, and suggests that the combination of maintained lawns, volunteer vegetation, and engineered retention basins as biophysical infrastructure trap substantial amounts of N. This suggests that human structures have not obliterated all biological processes that determine ecosystem function in this suburban catchment (Groffman *et al.* 2003).

Urban land use change decreases stream water quality. Urbanization is known to severely impact stream quality in many ways (Paul & Meyer 2001). However, we discovered that it is not always the densest and most intense form of urban settlement that has the greatest impact. Again, using BES long-term stream data, a surprising pattern has emerged. We maintain our focus on N loading, because of concern with it as a pollutant in drinking water and in the near shore marine or estuarine systems (Groffman *et al.* 2003). Given that Baltimore is located on the Chesapeake Bay, a large but fragile and highly impaired water body, N loading in urban streams is an increasing concern as urbanization spreads rapidly in Maryland and other tributary areas of the Chesapeake.

BES researchers discovered that the N loading in the forested stream was negligible, as expected. However, they discovered that suburban catchments had substantially and significantly higher loading than the dense urban settlement mixing row houses, commercial, and old industrial parcels near downtown Baltimore. The high loading in suburban streams may result from lawn runoff, septic inputs, or be a legacy of prior agricultural land uses. Preliminary results using stable isotopes of N to identify sources, suggest that the high suburban loading is a legacy of the agricultural land use that these particular suburbs replaced.

The third example of research results combines social and biophysical characteristics. It has been hypothesized that greenness of neighbourhoods is related to their socio-economic conditions. Grove (1996) tested this assumption by comparing vegetation cover throughout the Gwynns Falls watershed with an index of income and education derived from Census Bureau data. Furthermore, he compared data between the 1970 and 1990 censuses, which were the ones available to him at the time. His results show a good correlation between vegetation cover and high levels of income and education. However, the surprise was that the correlations were better between 1970 income and education and 1990 vegetation. The 1990 vegetation and social factors correlated less well with one another than the lagged correlation. This lag suggests that vegetation responds only relatively slowly to changes in the socio-economic conditions in a neighbourhood.

## CONCLUSION

Urban ecology has deep roots, although it has failed to flourish in mainstream ecology until now. This neglect by the profession of ecology has left a void that has been filled by other disciplines. However, these other disciplines have been focused either more narrowly than biological ecology – as in the case with botany or zoology – or have appropriately emphasized the core concerns of their focus – as in the case of social science, geography, economics or planning. This leaves much work still for biological ecology to do, and much still to contribute to the larger dialogue with other disciplines that have already claimed the territory of urban ecology. The prior claim on terminology is one reason that some ecologists, for example, M. J. McDonnell (pers. comm. 1991) prefer to speak of urban ecological research rather than 'urban ecology.' The slightly unfamiliar terminology – urban ecological research – is meant to emphasize that mainstream ecological science has both much to learn and much to contribute to the data base on urban ecosystems. Ecologists need to understand urban hydrology, nutrient cycles, disturbance, succession, biodiversity, and so on. But we also need to understand the social, economic, historical, engineering, and architectural controls and consequences of those ecological phenomena when addressed in the city.

Ecology, and indeed the term ecosystem, has been used metaphorically by many other specialties to indicate concern with a certain kind of environment, or with a certain suite of interactions. Ecology is defined as the science that studies the reciprocal relationships of organisms to their environment. Of course, ecologists mean environment in a particular way, as required by the focus on organisms. Social scientists, or historians, among others, also use the term environment. However, what specifically is intended by the term environment when used by those specialists likely differs from the things that ecologists would mean. Traditionally, ecologists mean to include such things as soil, water, climate and other organisms. Planners may include in the environment such things as economic, regulatory, and aesthetic variables. Social scientists may include cultural aspects, ethnic identities, or institutional structures among the environmental parameters used in a particular model. Economists may include international trade relations, and the activities of different sectors among their driving variables. Other disciplines would have their own favourite environmental parameters. Local residents include such things as crime and violence as parameters of their environment. Environment is context-dependent, discipline-dependent and perspective-dependent. Each discipline and stakeholder group has its own, legitimate idea of what the environment is.

It is clear that a systems perspective that can tie such diverse concerns together is needed. Ecologists are of course well versed in systems approaches. But as a discipline, there is much to learn and to contribute to systems models that give equal and serious attention to the concerns of bioecologists and to other disciplines, many but not all of which have been mentioned in this paper. We think that ecology should in fact play a central role in conceptualizing and studying the city. Without its contribution to the models and images of the city, attention to the underlying biologically driven processes, which ultimately support the metropolis, will be missing from the public dialogue. As more and more of the world's human population moves to cities, the call for sustainable cities becomes all the more urgent. If cities can be designed and operated to press more lightly on their regional ecological systems, and if ecological functions of nutrient, biomass, and water flow can be integrated more effectively into built and designed lands, then many benefits can accrue. These benefits can be reaped by urban dwellers, rural denizens, and the plants, animals, and landscapes in the hinterlands and downstream.

We hope the approaches we have outlined, and the integrative tools we have enumerated and illustrated using the BES, will prove useful to the globally crucial task of understanding the ecology of metropolitan systems, and to weaving the science of ecological research into the ongoing flow of interdisciplinary research on cities, and the public dialogue aimed at improving city life and impact.

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