Urban Ecology as an Interdisciplinary Field: Differences in the use of "Urban" Between the Social and Natural Sciences

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"If you wish to converse with me, define your terms." —attributed to Voltaire, The Home Book of Quotations: Classical and Modern, Fourth edition (B. Stevenson, ed.), p. 428, Dodd, Mead and Co., New York, NY, 1944

Abstract Though there is a growing appreciation of the importance of research on urban ecosystems, the question of what constitutes an urban ecosystem remains. Although a human-dominated ecosystem is sometimes considered to be an accurate description of an urban ecosystem, describing an ecosystem as human-dominated does not adequately take into account the history of development, sphere of influence, and potential impacts required in order to understand the true nature of an urban ecosystem. While recognizing that no single definition of "urban" is possible or even necessary, we explore the importance of attaching an interdisciplinary, quantitative, and considered description of an urban ecosystem such that projects and findings are easier to compare, repeat, and build upon. Natural science research about urban ecosystems, particularly in the field of ecology, often includes only a tacit assumption about what urban means. Following the lead of a more developed social science literature on urban issues, we make suggestions towards a consistent, quantitative description of urban that would take into account the dynamic and heterogeneous physical and social characteristics of an urban ecosystem. We provide case studies that illustrate how social and natural scientists might collaborate in research where a more clearly understood definition of "urban" would be desirable.

Keywords: Urban · social science · ecology · definition of "urban"

Introduction

There is now compelling evidence that humans are altering virtually all of the Earth's ecosystems. Vitousek *et al*. (1997) noted that more than half of the Earth's fresh water is used by humans, nearly half of the land surface has been transformed by human action, more atmospheric nitrogen is fixed by human activities than by all natural terrestrial processes combined, and human activities are leading to significant losses of biodiversity. As a consequence of these actions, most (if not all) ecosystems can arguably be considered human-dominated ecosystems, regardless of whether humans actually occupy (live within) them. However, humans are also creating new ecosystems specifically for dwelling: these are urban ecosystems (Stearns and Montag, 1974). These new, synthetic ecosystems are unquestionably human-dominated, and yet urban ecosystems are both qualitatively and quantitatively different from other human-dominated ecosystems in terms of development, sphere of

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influence, and potential impacts. Understanding these differences hinges on our ability to distinguish between urban and human-dominated.

In 1900, only 9% of the world's human population lived in "urban environments" (so called by the World Bank, 1984). This figure had increased to 40% by 1980, 50% by 2000, and is expected to increase to over 66% by 2025 (World Bank, 1984; Simpson, 1993; Rodick, 1995; Brockerhoff, 1996). The increasing abundance of such environments has not gone unnoticed by ecologists. Indeed, the "urban landscape is a well-appreciated form of landscape" (Weddle, 1986) and offers numerous areas of scientific study since urban landscapes are often characterized by the presence of exotic flora and fauna, an imbalance between biotic immigration and extinction rates (Rebele, 1994), and the presence of pollution in air, water, and soil (Botkin and Beveridge, 1997). Until recently, however, relatively little ecological research was conducted in urban settings. Indeed, ecologists have primarily sought to understand their subjects of study in the absence of humans and have usually considered humans chiefly as agents of disturbance (Pickett and McDonnell, 1993; Costanza, 1996). A recent survey of research papers in the foremost ecological journals between 1993–1997 revealed that only 25 of 6157 papers (0.4%) dealt specifically with urban species or were carried out in an urban setting (Collins *et al*., in review). Ecologists have recently begun to recognize this oversight, however, calling for more research into how overall ecosystem structure and function shape and are shaped by urban development (Matson, 1990; McDonnell and Pickett, 1990; Botkin and Beveridge, 1997; Walbridge, 1997; Parlange, 1998).

Such a pursuit is not as easy as it sounds, however. There are logistical problems incurred from working in urban settings, such as difficulty in obtaining permission to conduct large-scale experiments on private property, as well as vandalism to field equipment (see also Yalden, 1980). Similar problems are faced in most ecological studies. What is different about conducting research on how patterns of urbanization affect ecological processes, though, is in determining what constitutes an "urban ecosystem." By this, we mean recognition that an urban area is not simply a human-dominated area.

Fundamentally, a landscape defined as urban shows some effects of human influence. Taken literally, this could mean that the most remote sites could be called urban simply because humans have influenced a portion of their area at some point in time (e.g., by the presence of a secluded vacation cabin or even aboriginal ruins). Clearly, this description of urban is too broad to be very useful, and it confounds the differences between human-dominated and truly urban ecosystems. There is thus an evident need to remove the uncertainty with which ecologists define urban ecosystems and to correct oversights regarding definitions (or lack thereof) of what it means to be "urban."

In this paper, we will examine definitions of the term "urban" as used by ecologists and look towards the social sciences for guidance in creating a more quantitative description of what an urban ecosystem is. In recognizing that urbanization is both an ecological and a social phenomenon (thereby recognizing that urban ecology is an interdisciplinary field), we will compare and contrast definitions of "urban" as used by ecologists and social scientists and will provide some case studies of how interdisciplinary studies have defined and used "urban." This process will illuminate both strengths and gaps in current descriptions of urban systems. It will also provide both ecologists and social scientists with guidelines to quantify the urban setting of their own research projects. Although we recognize that no single definition of "urban" is necessarily more correct than another, we will demonstrate that demographic, economic, political, perceptive, and cultural criteria, when used in conjunction with geophysical and biological criteria, provide a more complete and useful definition.

How Ecologists have used the Term "Urban": a Review

Ecology studies the relationships between organisms and their environments. To determine how ecologists have described urban environments, we reviewed 63 ecological journal papers (Appendix 1). Using the Institute of Scientific Information's Web of Science database (http://www.isinet.com), we located research papers with "urban," "urbanization" (including British spelling of "urbanisation"), "city," "cities," "metropolis," or "suburb" in the title, abstract or keywords. For each reference, we noted whether "urban" was defined (and if so, what the definition was). We included only papers that considered how urban environmental features affect the abundance and distribution of organisms other than humans (the traditional focus of ecology), excluding papers that dealt strictly with environmental health/medicine, epidemiology, pest management, or ecotoxicology in urban settings. Excluding papers from these disciplines made our review potentially more relevant to both basic and applied research questions about urban ecosystems in general, whereas environmental health/medicine, epidemiology, pest management, and ecotoxicology are often localized in focus to meet specific applications. We did not exclude papers that assessed biodiversity along gradients of pollution, for example, merely because such papers included a variable that happened to be potentially of interest to environmental health/medicine, epidemiology, pest management, or ecotoxicology. Rather, we included papers based on the criterion of whether the primary research focus was ecological. While we acknowledge that other natural sciences (and, generally speaking, other sciences) may provide important insights in the study of urban ecosystems, we feel that ecology is the foremost and most inclusive of these, based simply on the definition of ecology. As with any review, particularly on a topic as diverse as urban ecology, it is likely that we overlooked some appropriate papers. However, the sheer volume and variety of papers that we did uncover should provide a reasonable assessment of how ecologists have used the term "urban."

Types of Ecological Studies in Urban Environments

Cicero (1989) identified four types of ecological studies in urban environments, of which we found examples of each (detailed below): (1) comparison of different land-use types within an urban setting (e.g., Woolfenden and Rohwer, 1969b; DeGraaf and Wentworth, 1981), (2) comparison of an urban area with a nearby "natural" area (e.g., Woolfenden and Rohwer, 1969a; Emlen, 1974; Guthrie, 1974), (3) gradient analysis (e.g., Klausnitzer and Richter, 1983; Ruszczyk, 1986; Ruszczyk *et al*., 1987; Sustek, 1987, 1992, 1993; Ruszczyk and de Araujo, 1992; Goszczynski *et al*., 1993; Pouyat *et al*., 1994; Medley *et al*., 1995; Blair, 1996; Natuhara and Imai, 1996; Blair and Launer, 1997; McDonnell *et al*., 1997), and (4) studies of urban development dynamics by monitoring a single area over time (e.g., Erz, 1964; Walcott, 1974; Rosenberg *et al*., 1987). In addition to these four types of urban ecological studies, there is also ecological "footprint" analysis (Rees, 1996; Wackernagel and Rees, 1997).

Comparisons within an urban setting—these studies acknowledged that a city is heterogeneous in space, meaning that an urban environment is a mosaic of areas that have different physical properties and uses (Hohtola, 1978; Dulisz and Nowakowski, 1996; Hadidian *et al*., 1997; Sewell and Catterall, 1998). In terms of comparing different land-use types within an urban area, relatively few studies calculated structural variables such as percent vegetative cover, average building height, or housing density (e.g., Ruszczyk *et al*., 1987; Edgar and Kershaw, 1994; Friesen *et al*., 1995; Blanco and Velasco, 1996; Natuhara and Imai, 1996). More usually, the researchers defined the urban environment in terms of generic land-use categories, such as "residential yard" or "park" (e.g., Hooper *et al*., 1975; Weber, 1975; Huhtalo and Jarvinen, 1977; Hohtola, 1978; Goszczynski *et al*., 1993; Jokimaki and Suhonen, 1993; Mirabella *et al*., 1996; Hadidian *et al*., 1997; Sewell and Catterall, 1998).

"Urban" vs. "natural"—these studies made comparisons between urban areas and undeveloped rural areas outside a city (Woolfenden and Rohwer, 1969a; Emlen, 1974; Guthrie, 1974). These studies assumed that the undeveloped areas represented regions outside human influence, with "urban" characterized by the presence of humans and "natural" by their absence. "Urban" and "natural"

environments were thus viewed by ecologists as being at opposite ends of a spectrum, representing a dichotomy of history, structure, function, and value (McDonnell *et al*., 1997; Walbridge, 1997).

Gradient analysis—in these studies, the ecological effects of urbanization were assessed along a gradient (usually simply the distance from a city's geographic center and not quantified as a gradient of variables such as housing density, air quality, etc.). With a gradient approach, the potential difficulty in assigning clear boundaries to urban ecosystems is recognized implicitly. In its most literal sense, gradient analysis invokes a spatially continuous linear gradient from urban core to rural exterior, as envisaged in simple models such as the concentric theory of urban structure and growth (Park *et al*., 1925). Biotic, physical, and social variables (e.g., human population density, housing density, traffic volume, air quality, species richness) are then correlated with position along this gradient. Distance from the urban center often provides a useful first cut for determining whether spatial correlations exist between increasing human activity and ecological response variables, with more proximate explanatory variables and mechanisms left for more detailed follow-up studies.

Many cities, however, particularly those that have developed in the last 10–20 years, consist of multiple cores, have hard boundaries, and grow by rapid, leap-frog development over remnants of undeveloped open space. Moreover, some urban-related effects do not decrease in intensity in a simple linear or concentric pattern from a single center. For example, the patterns of urban air pollution derived from fossil fuel combustion frequently occur in "complex terrains," where synoptic and topographically controlled airflows lead to patterns in the concentrations of nitrous oxide, fine particulates, and low-level ozone that may show little correspondence to the spatial distribution of urban core areas (Plaza *et al*., 1997; Sillman, 1999; Ellis *et al*., in press). In such situations, there is not a simple linear decrease in urbanization with distance from the city center. A more indirect form of gradient analysis is therefore necessary, whereby ecological variables are measured and used to construct a gradient of urbanization from sites dispersed across an urban area (e.g., Medley *et al*., 1995; McDonnell *et al*., 1997). In such cases, having easily quantifiable, independent criteria by which the urban gradient is defined is particularly important. Although gradient analysis is useful in pointing out that the influences of urbanization are continuous and not binary, the lack of gradient quantification we observed in most studies was disturbing. In addition, applications of gradient analysis to date have simply correlated environmental disturbances to aggregated or very simple measures of urbanization (Alberti, 1999).

Urban succession—Very few studies examined how ecological patterns and processes in urban mosaics change over time or attempted to quantify rates of change in the urban setting and compare how these rates differed from the same processes occurring in semi-natural and natural ecosystems (Walcott, 1974). In those studies that did consider a temporal component to urbanization, urbanization was seen as a form of disturbance, creating a "natural experiment" (*sensu* Diamond, 1986). Disturbance from urbanization was then treated in a similar fashion to effects from fire or flood, allowing comparisons to be made between disturbed and undisturbed areas or over time in a single area (pre-disturbance vs. post-disturbance) (Erz, 1964; Rosenberg *et al*., 1987).

Ecological "footprint" analysis—ecological economics attempts to view "socioeconomic system(s) as a part of the overall ecosphere, emphasizing carrying capacity and scale issues in relation to the growth of the human population and its activities" (Costanza *et al*., 1997). As an extension of ecological economics, ecological "footprint" analysis seeks to convert the material and energy flows required to sustain the human population and industrial metabolism in a defined area (regional, national, or local, e.g., a city) into a land/ecosystem area equivalent (Folke *et al*., 1997; Rees, 1996). That is, rather than considering the impact of a concentrated population only on its immediate surroundings, ecological "footprint" analysis takes into account the effects of humans on both their immediate surroundings and areas of influence much further afield. In "footprint" analysis, cities are typically defined as areas dominated by "consumed or degraded land", i.e., the "built environment" (Wackernagel and Rees, 1997). Defining boundaries in this way has been a source of criticism, particularly where a large urban region cuts across natural ecosystem boundaries (van den

Bergh and Verbruggen, 1999). More consistent and interdisciplinary ways of defining what is urban would benefit "footprint" analysis and help to resolved problems of comparability of data between disciplines.

These five types of urban ecological studies represent different approaches to a common subject. Shortcomings with how "urban" was defined were found in all five types.

Some Problems with Definitions of "Urban" in Ecology

For the vast majority of the papers we reviewed, the definition of what was urban was simply assumed, not defined explicitly, in much the same way that the definition of "forest" is assumed to be known to readers. Where the system was defined at all, it was usually done using general and indefinite terms (Table 1). For example, consider this statement: "The term 'urbanization' refers to development . . . such as road and building construction, and other changes of land use from rural to residential and industrial that result in an increase of impermeable surface, accumulation of toxic substances, increase of domestic wastewater load, and increase in water demand due to increased human population . . ." (Kemp and Spotila, 1997). In the field of urban landscape planning, a typical definition of "urban" is similar to that given by Hendrix *et al*. (1988): "All residential land at densities greater than one dwelling unit per acre, all commercial and public institutions, railyards,

Table 1 Examples of how "urban" has been defined in ecology and in various social sciences, with some strengths and weaknesses of each definition

Discipline	Reference	Definition of "urban"	Strengths	Weaknesses
Ecology	Emlen, 1974	Area consisting of "houses and lawns"	Mentions specific features	does not include density
Ecology	Erskine, 1992	"Built-up" area	Brief	Vague
Ecology	Odum, 1997	Area that uses at least $100,000\,\mathrm{kcal/m^2/yr}$	Based on international currency	Difficult to measure accurately
Sociology	U.S. Bureau of the Census	Area with > 2500 people (620 individuals/km^2)	Precise, includes population density	Arbitrary
Sociology	United Nations, 1968	Area with > 20, 000 people	Precise	Arbitrary; does not include density
Economics	Mills and Hamilton, 1989	"A place [with] a minimum population density [and] also a minimum total population"	Accounts for both human abundance and density	Does density not specify the minimum density or total population
Environmental psychol-ogy	Herzog and Chernick, 2000	Area with a "driveway between buildings . . .[and] paved parking areas with older buildings in the background"	Emphasizes presence of human-built structures (especially those associated with transportation)	Does not include direct presence of humans (only indirect) or human density
Planning	Hendrix *et al*., 1988	"All residential land at densities greater than one dwelling unit per acre, all commercial and public institutions, railyards, truckyards and highways"	Includes goods-and service-providers, transportation elements, and dwellings at a specified density	Density is arbitrary, boundaries are unspecified

truckyards and highways." Such definitions are thin and do not allow results to be compared adequately between different urban systems that may have different attributes. In another typical case, "urban" was defined as simply "built-up" (Erskine, 1992). In still another paper, "urban" referred to any area under human influence, such as a managed orchard in a rural setting (Majzlan and Holecova, 1993). Such variety in how these terms were used indicates a lack of consensus on what is meant by urban, resulting in a lack of rigor in the use of terminology (see Mack, 1999 for a discussion of how lax usage of terminology in ecology in general has created problems in the processes of peer review and publication).

Our review thus revealed that most ecological studies of urban environments have treated cities as another biome, an anthropogenic analog of a desert or temperate forest (Botkin and Beveridge, 1997). However, whereas "natural" biomes are defined by ecologists on the basis of variables such as temperature, precipitation, soil, and dominant vegetation types, urban environments appear to be determined solely on the basis of human presence. Urban studies assumed that such an environment would simply be recognized without needing to be defined clearly, with characteristics of the urban environment therefore usually not quantified. More often a qualitative (categorical) approach was used, usually based on simply the presence of human constructions. This vagueness precludes comparative studies from being made with any degree of precision.

However, there were some rare and relatively recent exceptions to this lack of urban quantification (e.g., Ruszczyk *et al*., 1987; Ruszczyk and de Araujo, 1992; Edgar and Kershaw, 1994; Friesen *et al*., 1995; Medley *et al*., 1995; Blanco and Velasco, 1996; Natuhara and Imai, 1996; and Blair and Launer, 1997). These studies measured a variety of physical (and some socioeconomic) variables, usually along a gradient of urbanization (usually density of people or buildings). We also noted a related trend in how urban ecosystems were considered over time. Earlier studies were largely descriptive and examined plants or animals that happened to occur in cities, whereas more recent studies have been more quantitative and were established within an urban ecology framework (ecology *of* urban ecosystems as opposed to ecology *in* urban ecosystems, *sensu* Fisher, 1997). Despite this trend, there is still a dearth of published studies that deal explicitly with urban ecology. Approximately half of the papers (46%) we reviewed were written before 1990, indicating that there has been interest in urban ecology for some years. Indeed, as early as 1935, there was a plea for ecologists to integrate human effects into their discipline (Adams, 1935). Serious scholarly interest in urban ecology thus evidently occurred rather early on in ecology, but preoccupation with the world wars, limited funding, and a lack of technological sophistication needed to address issues at city-sized spatial scales (e.g., remote sensing technology) may have precluded advancement of the field until recently (see also Adams, 1940; Lindeman, 1940). Accelerating human population growth, however, has made the issue immediately pressing (Pickett and McDonnell, 1993).

Most strikingly noted, however, was the fact that the majority of the studies we examined lacked an explicit understanding of the socioeconomic components of an urban system. Unlike ecology and other natural sciences, the social sciences were developed expressly for the purpose of examining human systems. Therefore, we culled definitions and techniques from a variety of social sciences that will help ecologists integrate social variables in ways that are appropriate for their own unique research aims. Although there exists much social science literature that possesses only a tacit understanding of what urban means (as in much of the ecological literature), we present attributes that characterize urban settings that are routinely included in social science studies and suggest a place for them in ecological studies.

Taking Cues from the Social Sciences

The social sciences (including, but not limited to, anthropology, political science, economics, planning, sociology, and environmental psychology) provide many examples of how urban areas have been defined in their respective disciplines (see, for example, Macura, 1961). Social scientists routinely distinguish among the terms “urban place,” “urbanized area,” “metropolitan statistical area,” and “city,” all of which are considered “urban” (Mills and Hamilton, 1989). The qualitative analysis of definitions of “urban” in social sciences provided here is meant to be neither comprehensive nor representative of all social science understandings of what is urban. Rather, our intent is to introduce the reader to some representative definitions of what is urban to social scientists and to introduce the idea that even within the social sciences, how and why “urban” is defined varies.

There are some standardized definitions of “urban” that are often used in the social sciences, but even these standardized definitions vary (Table 1). For example, the U.S. Bureau of the Census defines “urban” as an area with more than 2500 people (>620 individuals/km^2; http://www.census.gov/population/censusdata/urdef.txt). The United Nations, on the other hand, defines “urban” as an area with more than 20,000 people (United Nations, 1968, p. 38). These numbers are somewhat arbitrary and thus necessarily incur problems (e.g., is an area with 19,999 people substantially different from a truly “urban” site?), but they do provide useful boundaries. Indeed, “urban” does not necessarily need to refer to a concretely quantifiable category; the important point in defining what is “urban” is to provide a relative benchmark with which to compare studies.

Differences in the description of “urban” within the social sciences focus on various points of interest, often to the exclusion of attributes of interest to another discipline (Table 1). For example, an economist may refer to an urban area as “a political unit that generally contains more than 25,000 individuals . . . [where] increases in urbanization just mean increases in the share of the population living in these political units” (Glaeser, 1998, p. 2). This definition of urban is based on human population density within a given political unit. Another definition, however, may refer to a city more casually and state that “a city is just a dense agglomeration of people and firms” (Glaeser, 1998, p. 140), a definition that also notes density (although its exact measure is left unspecified), but with a nod towards the institutions that make up the urban framework.

A regional planner may take a more descriptive approach in defining what is urban, paying more attention to the structural divisions of urban areas:

> Our image of a city consists not only of people but also of buildings—the homes, offices, and factories in which residents and workers live and produce. This built environment forms contours which structure social relations, causing commonalities of gender, sexual orientation, race, ethnicity, and class to assume spatial identities. Social groups, in turn, imprint themselves physically on the urban structure through the formation of communities, competition for territory, and segregation . . . (Fainstein, 1994, p. 1)

A sociologist may use an even broader description that focuses on the presence of certain signposts that we culturally associate with cities (e.g., presence of centers for performing arts) or density-dependent differences in relationships among people (e.g., greater number of contacts with others, more secondary rather than primary relationships, and degrees of division and specialization of labor; Forman and Godron, 1986).

Results from empirical research in environmental psychology suggest that people perceive and conceptualize “urban” and “natural” environments differently (Kaplan *et al*., 1972; Kaplan, 1987; Herzog, 1989). Results of studies that focused on the perceived content of urban and natural environments and research on the relationships between environmental complexity and preference for certain environments (e.g., Kaplan *et al*., 1972; Kaplan, 1987) suggest that the mental categorization of landscapes into groupings such as “urban” and “natural” is based on different cognitive and affective criteria and content domains. For example, by using measures of brain-wave patterns, heart rate, and other physiological variables, Ulrich (1981) and Ulrich et al. (1991) found that scenes of non-developed (natural) environments have a more positive influence on human emotional states and stress levels than do urban scenes. The implication of these studies is that humans apparently perceive and react differently to natural versus urban settings, and therein lies yet another way by which a social scientist may define “urban.” Since perceptions are integral to people’s motivations and actions, using a perceptually based definition of urban provides a key link in the cultural, political, physical, perceptual, and economic aspects that must be integrated in urban ecology. If the definition of “urban” incorporated perceptual variables known to be salient to a person’s discrimination between urban and natural environments, then the definition may be useful to interdisciplinary approaches to urban ecology.

To be sure, these definitions and descriptions of “urban” in social science disciplines are neither all-encompassing nor necessarily representative of their respective disciplines, but they are a reflection of the varied factors found in social scientists’ understanding of urban areas: these definitions ask us to reflect upon the cultural and socioeconomic as well as the physical setting in defining an urban ecosystem.

Integration of Social and Natural Science Definitions of “Urban” in Urban Ecology

In order to characterize the many physical, cultural, and socioeconomic characteristics of urban areas, a researcher must have certain social science skills and resources, which we do not expect all ecologists to possess. The best solution to this conundrum is collaboration between natural and social scientists, but even in circumstances where this is not possible it still remains within the means of ecologists to include quantified descriptions of their urban study sites. We can agree upon factors that constitute urban and agree to describe certain physical and socioeconomic and political aspects of a place as we seek to develop comparative urban studies. There are a number of potential attributes that could be used to quantify and define what urban means. So that there is comparability among independent research efforts, we propose that researchers describe the following attributes of their urban study sites:

Demography—a demographic description may work well at the large, whole-system scale. However, at a more detailed, within-city level, some demographic patterns may be misleading. For example, wealthier parts of cities may have relatively low human density but have a structure and function that is urban in other respects. The necessary variables to assess demography are:

- population density (e.g., by age, income level, etc.)
- economic characteristics (e.g., average housing value)
- governance type

Physical geography—based on one or several common attributes of urbanization, including:

- area (e.g., U.S. Bureau of the Census’s Primary Metropolitan Statistical Area)
- growth pattern (see Ewing, 1997; Forbes, 1997)
- distance to other urban areas
- description of urban morphology (protocol in Weitz and Moore, 1998)
- study scale (grain and extent; Kotliar and Wiens, 1990)
- historical, current, and adjacent land-use types
- land-cover type
- age since conversion from indigenous habitat
- housing type and density
- road type and density
- traffic frequency

Ecological process rates—based on locating where rates of ecological processes change rapidly. For example, it is already well established that fossil fuel combustion increases nitrogen and sulfur deposition across large areas within and adjacent to industrial areas, which leads to increases in net nitrogen availability, nitrification, and nitrate leaching (Aber, 1993). Rapid assays of such changes could be used to delimit the urban system.

Energy—the feature that distinguishes an urban ecosystem unambiguously from its surroundings is the level of energy use, with the amount of energy consumed per unit area per year in an urban environment being at least an order of magnitude greater than in other ecosystems (Odum, 1997). For example, data from Brussels (Belgium) have shown that in addition to the annual natural radiation inputs of 58×10^{12} kcal/yr, there is an additional energy use of 32×10^{12} kcal/yr from fossil fuel combustion, more than half the natural total (Sukkopp, 1990). A distinguishing characteristic of urban ecosystems is thus the high levels of energy use per year per area, largely derived from the combustion of fossil fuels, that is required to construct and maintain the urban infrastructure. Thus, although urban areas cover a relatively small percentage of the Earth's surface, they represent "hot spots" of energy use. Although in practice it may not always be easy to obtain detailed estimates of annual energy use, the advantages of using energy to define urban from other ecosystems are several. First, annual energy use could be used to place urban ecosystems in context with non-urban but human-dominated systems (e.g., agroecosystems). Second, a measure of annual energy use provides a means of defining urban systems independently of culture and uses units (e.g., kilocalories/km^2/yr) that have international currency. Third, since there is a monetary cost involved in producing energy for human use, energy units can be translated into local monetary units and hence serve as a means of linking ecological and socioeconomic studies.

Our approach focuses on urban properties that can be measured directly and relatively quickly and easily. Researchers should not be limited by this list and should add other important attributes as they see fit. In addition to these socioeconomic data, researchers should maintain an extensive and on-going pictoral inventory of their study site. This will aid in keeping track of changes in rural-to-urban conversion, urbanization, and allow the opportunity to test human perceptual and conceptual responses to changes in the landscape under study (Palmer and Lankhorst, 1998). Some of the data listed above are categorical (e.g., type of urban morphology, some land-use characteristics, growth pattern, and governance type) and are therefore amenable to a checkbox-style datasheet. Some of the data are relatively easy to obtain. For example, U.S. demographic data are widely available at university and local libraries as well as over the Internet (http://www.census.gov). Land use and growth information are generally available from a local planning office. These attributes can then be used to characterize three fundamental aspects of urbanization which determine when "rural" becomes "urban": timing, dynamics, and boundaries (Pond and Yeates, 1994).

There are some precedents in the existing ecological literature where social factors were incorporated into ecological studies, such as human population density, traffic volume, and land use (e.g., Medley *et al*., 1995; McDonnell *et al*., 1997; Wear and Bolstad, 1998). However, these studies were the exception rather than the norm. There were numerous cases where an ecological study would have been strengthened had it quantified the urban area in detail and included an explicit definition of "urban." For example, Faeth and Kane (1978) research examined how the number of flies and beetles in parks in Cincinnati, Ohio (USA), varied with park size. They found that species richness and abundance were positively related to park size, but there was some variation in these responses. Faeth and Kane did not quantify the parks individually, nor did they quantify the setting surrounding each park. It is possible that the parks' physical and socioeconomic surroundings affected the species present, but without inclusion of urban variables relating to park context, this remains uncertain.

Because an urban environment is both a physical and a social entity in its creation, functioning, and future, an in-depth understanding of what constitutes an "urban" ecosystem requires integration of natural and social sciences (Stearns and Montag, 1974; Pickett and McDonnell, 1993; Pickett *et al*., 1997). Each discipline would be strengthened if it were to include variables usually attributed to the other. We thus recommend that social scientists include a more ecological description of "urban" in their work, because information on the ecological status of cities may be very informative to various social aspects of urban life (e.g., quality of life, or purchasing or mobility decisions made by people of different socioeconomic levels). For example, information about the occurrence and abundance of scorpions (a household pest with a potentially lethal sting) in Phoenix, Arizona (USA), may be useful to homeowners by informing them of scorpion-prone areas and to urban planners in deciding where future development in Phoenix should occur so as to minimize human-scorpion encounters (McIntyre, 1999). The field of urban ecology would thus greatly benefit from reciprocity. To illustrate this kinds of understanding we may gain from interdisciplinary, reciprocal urban research, we outline two case studies below.

Case Studies of Integrative Urban Ecology

Vegetation Structure vs. Socioeconomic Index in Baltimore, Maryland (USA)

The work of Grove and Burch (1997) highlights some features of how an integrated approach to the study of urban ecosystems can bring about an understanding not possible with a single disciplinary approach. Grove and Burch (1997) research explored the reciprocal relationship between social differentiation (land use and residential stratification) and vegetation structure. Their study focused on how spatial patterns of urban development and land-use dynamics have influenced cycles and fluxes of critical resources (e.g., energy, materials, nutrients, genetic and nongenetic information, population, labor, and capital). A particular focus of their research was how differential access to and control over critical resources affect the structure and function of urban ecosystems. The overall study area was the Gwynns Falls watershed in Baltimore, MD (USA), a naturally defined urban-rural catchment area, combining the ecosystem/watershed approach of Bormann and Likens (1979) with social ecology theory and a community forestry perspective (e.g., Cernea, 1991). The degree of urbanization was defined in terms of land use and population density. The research differed from the usual studies of environmental equity in that it focused on the impacts of a diffuse set of drivers (e.g., private markets, government agencies, and local residents) over an entire watershed, rather than being restricted to a limited set of factors and environmental conditions usually related to point sources of pollution (e.g., Bullard, 1990).

Grove and Burch developed vegetative and socioeconomic indices for the city of Baltimore to explore the linkages between socio-cultural and biophysical patterns and processes on a spatially explicit basis. Characterization of patches within the watershed was achieved using a limited number of representative indicators. The socio-cultural indicators were obtained from the U.S. Bureau of the Census (at the block group level) and included socioeconomic (based on % professional/managerial workers, household earnings, and % with college degree), household (% married, % one-family households, % owner-occupied dwellings), and ethnicity (% non-white and foreign-born) indicators, which were used to derive a “social area index.” Vegetation in the area was simultaneously described based on whether the ground surface was impervious or not (i.e., had vegetation cover) and whether it had a tree canopy or not. One of Grove and Burch’s main findings was that after accounting for variations in population density, there is a positive relationship between the likelihood of a community to contain areas with trees and grass and its level of income and education. This study used a continuous definition of “urban” that was based on human population density, socio-cultural variables such as household income and education level, and the presence of anthropogenic landscape alterations (such as the presence of pavement). Without this multifaceted definition, Grove and Burch would have been unable to uncover the linkage between the structure of people’s surroundings and their socioeconomic status.

Urban Water Balance for a Portion of Vancouver, British Columbia (Canada)

The hydrology of urban ecosystems differs significantly from many other ecosystems in that there is a piped water supply, organized water disposal, and changes in infiltration due to the increased coverage of impervious surfaces and water addition due to irrigation. Grimmond and Oke (1986) investigated the relationships among various elements of the hydrological cycle and urban conditions. Daily, monthly and annual water balance components for a catchment in Vancouver, BC (Canada), were compared to those from a rural area to elucidate the effects of urban development. The study site was the Oakridge catchment, a residential area in Vancouver. Observations in the catchment included daily totals of water used by the households, precipitation amounts, weekly soil moisture measurements, and estimates of soil water storage capacity. An overall water balance (i.e., inputs versus outputs versus changes in storage) was calculated for an entire year, as well as changes in these terms on a seasonal basis. The system consisted of two main components, the internal system (inputs of piped water to homes and output of waste water via sewers) and the external system (the "people-modified" hydrologic system, which included modifications of surface cover such as removal of natural vegetation, paving over of soil, artificial drainage networks, garden irrigation, swimming pools, street cleaning, storage ponds, reservoirs, and changes in precipitation and evapotranspiration brought about by the effects of urban modification on climate).

The results revealed the importance of understanding the roles of human behavior and perceptions in the overall water balance of the catchment. In the colder half of the year, total human water use was constant and variations in the water balance could be attributed to basic hydrologic parameters. During the summer months, however, the pattern of water use was much more variable and was related to prevailing weather conditions, the role of irrigation in yards, and a feedback mechanism between these two factors. This variability was primarily due to the residents perceiving a need to supplement the precipitation during periods of increased temperatures and/or solar radiation. There was a strong statistical relationship between human water use and weather—66 to 72% of water use during this period was explained by air temperature alone; the addition of the number of days since precipitation, soil moisture, and net radiation improved this to 85%. The authors concluded that the processes involved were more than a physical cause-and-effect system; rather, the system involved human decision-making and action (to water or not to water the yard) indirectly linked to weather patterns via a perception and assessment of the need for water. Interpretation of the results revealed the role of irrigation (especially yard watering), prevailing weather conditions (particularly evapotranspiration) and the complex feedback system between human behavior and biophysical controls. This urban study thus linked human population and behavior to resource use.

Concluding Remarks

Most of the ecological papers we reviewed were simply traditional plant or animal ecological studies conducted in urban settings, with humans considered to be agents of disturbance. However, urban ecology implicitly recognizes the role that humans play in developing unique ecosystems (Parlange, 1998), because urbanization is both an ecological and a social phenomenon. Therefore, integrating both social and natural sciences in the study of urban ecosystems is crucial, making urban ecology a truly interdisciplinary field (Walbridge, 1997). One difficulty in this integration lies in the fact that the term "urban" is used differently by social and natural scientists. Social scientists use the term to refer to areas with high human population density, whereas ecologists use the term more broadly to refer to areas under human influence.

As research into urban ecosystems expands, the need for an unambiguous, quantitative definition of urban becomes more apparent. Such a definition poses a problem, however. Although the development of a predictive (*a priori*) way of defining urban environments may be more desirable than the current descriptive (*a posteriori*) mode, it is probably not feasible for two reasons. Foremost of these reasons is the fact that the description of urban depends on the research question being asked. A certain urban variable may exist at an inappropriate scale for some questions. For example, a variable such as average building height may exist at too coarse a scale to be useful in answering a question like "how do the population dynamics of soil nematodes differ in areas with paved roads versus unpaved roads?" even though it may be quite appropriate for a question such as "do monarch butterflies avoid areas with tall buildings during migration?". Secondly, the boundary between the urban environment and the surrounding landscape is often not a clear one, but rather a gradient from an increasingly disturbed natural or agricultural system to increasingly dense suburban to urban core.

Recognizing these difficulties, we recommend that at least a working definition of the "urban environment" be included in each study, explicitly including baseline information on demography, physical geography, socioeconomic, and cultural factors that can potentially explain existing urban structure and predict trajectories of urban growth. A description of the urban environment should be as quantified as much as possible to facilitate comparisons among studies and areas, as would be needed for repeating a study in a different location or at a different time. We have suggested an interdisciplinary approach whereby ecologists borrow heavily from social sciences to construct a definition of their research setting. Likewise, social scientists would benefit from this same sort of consistency in defining their study systems.

Despite the clear need for the focus of ecological research to be turned towards human-dominated systems and particularly urban ecosystems (McDonnell and Pickett, 1990), there is relatively little research activity in this area. There is thus an unprecedented opportunity for research in urban ecosystems, especially considering that urbanization is increasing in both scope and magnitude (Botkin and Beveridge, 1997). Without a more quantitative definition of "urban," however, progress in urban ecology will be made slowly.

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Appendix 1. Ecological Research Papers that were Reviewed

Blair, 1996
Blair and Launer, 1997
Blanco and Velasco, 1996
Botkin and Beveridge, 1997
Cicero 1996
Clark and Samways, 1997
Czechowski, 1982
Davis, 1978
DeGraaf and Wentworth, 1981
Dreistadt *et al.*, 1990
Dulisz and Nowakowski, 1996
Edgar and Kershaw, 1994
Ehler and Frankie, 1979a,b
Emlen, 1974
Erskine, 1992
Erz, 1964
Faeth and Kane, 1978
Frankie and Ehler, 1978
Friesen *et al.*, 1995
Goszczynski *et al.*, 1993
Guthrie, 1974
Hadidian *et al.*, 1997

Hohtola, 1978
Hooper *et al*., 1975
Huhtalo and Jarvinen, 1977
Jim, 1998
Jokimaki and Suhonen, 1993
Jones and Clark, 1987
Kemp and Spotila, 1997
Klausnitzer and Richter, 1983
Kozlov, 1996
Lancaster and Rees, 1979
Majzlan and Holecova, 1993
McDonnell and Pickett, 1990
McGeoch and Chown, 1997
McIntyre, 1999
Medley *et al*., 1995
Mirabella *et al*., 1996
Natuhara and Imai, 1996
Natuhara *et al*., 1994
Nowakowski, 1986
Nuorteva, 1971
Pouyat *et al*., 1994
Rebele, 1994
Rosenberg *et al*., 1987
Ruszczyk and de Araujo, 1992
Ruszczyk *et al*., 1987
Sewell and Catterall, 1998
Speight *et al*., 1998
Sustek, 1987, 1992, 1993
Tischler, 1973
Trojan, 1981
Vincent and Frankie, 1985
Walcott, 1974
Wear and Bolstad, 1998
Weber, 1975
Woolfenden and Rohwer, 1969a,b
Zapparoli, 1997

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