Toward Ecosystem Management: Shifts in the Core and the Context of Urban Forest Ecology

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Abstract The core of urban forest ecology is the body of scientific knowledge found in the literature. The formation of this core began in the 1950s and 1960s and took shape in the 1970s and 1980s with formal studies of structure and function. During the following ten years, the idea of the urban forest ecosystem was introduced, and is now the basis for further development of the scientific core. The context for this core is provided by statements of public policy and perceptions of land management needs. An important shift is occurring in context as land management organizations, ranging from urban-based alliances to state and federal agencies, embrace the ecosystem concept as an approach to understanding and governing complex mixtures of biophysical and human phenomena using a hierarchy of time and space scales. This rapid shift in context places a burden on the scientific core to articulate and test models of urban forest ecosystems. To accomplish this, an approach to research is needed that will help us understand how urban, periurban, and exurban lands interact functionally with other components of the larger landscape. Part of this approach requires scientists and managers to develop a common vocabulary and set of realistic expectations to confront problems of systems complexity and uncertainty.

Keywords: urban forestry · ecosystem management · policy · land management · deforestation · afforestation · complexity · uncertainty

Both the core and the context of urban forest ecology are changing. The core is evolving slowly from a body of studies focused on structure and function to one including the ecosystem concept. The public and political context is shifting more rapidly to embrace the ecosystem approach to land management in both urban and wildland regions. The ecosystem approach is explicitly "science based." The question is whether resource science in general and urban forest ecology in particular are equipped to provide the support necessary to implement ecosystem management. The fact that ecosystem science and the antecedents of ecosystem management have historically dealt with nonurban areas exacerbates the problem for urban forest ecology.

A preliminary definition of terms will serve as a point of departure. The *urban forest* is all the vegetation in an urbanized area. The *periurban* area immediately surrounds the urban forest, and the *exurban* area is the larger hinterland into which people are migrating from urban and periurban zones and from which resources for the city are taken. Rather than defining three separate areas, it is more realistic in many regions to think in terms of a gradient of "urbanness" (e.g., population or building/road density) from a high in the city to a low in the exurban hinterland. The *core* of urban forest ecology is the body of scientific literature that develops concepts and methods, explicates

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principles, and interprets empirical results. It focuses on relations among vegetation, soils, wildlife, water, energy, the atmosphere—and, of course, humans.

The *urban forest ecosystem* is a concept that enlarges the scope of the urban forest to include humans. People are not part of the urban forest but they are part of the urban forest ecosystem. The ecosystem concept also enlarges our temporal and spatial scales of concern. As such, it is an accounting system that requires us to examine how our actions produce costs and benefits not only within our ecosystem but in ecosystems linked to ours across large units of space and time. The urban forest ecosystem is a concept that requires us to understand ecosystem processes that produce changes over time. These changes occur gradually (the aging of trees) and episodically (a large urban fire in the Oakland-Berkeley hills of California).

The *context* of urban forest ecology comprises the public policy and implementation strategies that inform scientists about the needs of land managers to have useful concepts, methods, and management approaches. This context also provides scientists with data about how forest ecosystems are operating and the constraints and opportunities of management. Thus core and context must interact functionally: science informs policy, and the implementation of policy informs science. The scientific core does not operate in isolation of public perceptions about such concerns as the value of science, what is good in nature, and the complexity and uncertainty in this world.

In the sections following, I first restate the problem of urbanization and forests, then describe how urban forest ecology has addressed that problem. Questions and conceptual dilemmas emerge from the gap between the problem and where the core of science stands today. The gap can be closed, and the science can become more capable of answering fundamental questions, if a more systems-oriented approach is taken in the research. This approach can better nurture the development of both the scientific core and the public policy context of urban forest ecology. The theme of this book is integration, and this chapter examines the potential for integrating core and context so that the combined human effort invested in science and management achieves a higher degree of efficiency.

Phenomenon and Problem: Deforestation and Afforestation During the Course of Urbanization

As people migrate, settle, and establish economic and social organizations, these activities change the soil and vegetation with consequences that we do not fully understand, even though we have been asking questions about the human impact for more than a century. These consequences distribute themselves at various scales of time and space, among different types of people as benefits and costs expressed in both monetary and nonmonetary terms. We are changing landscapes daily without knowing the magnitude and distribution of these costs and benefits. It is not just *deforestation* for roads, cities, and industry that is of interest to us, but also the processes of *afforestation* of urban lands, and of derelict and discarded lands. By a combination of both removing and planting trees, our society is changing the functioning of whole ecosystems and the course of global ecological evolution.

During the last fifty years, scientists have addressed the dynamics of vegetation and soil changes in natural ecosystems. But now it is difficult to find an ecosystem that has not been influenced by humans. This knowledge about natural ecosystems is slowly being augmented with research on how human land uses related to urbanization change vegetation and soil attributes that in turn modify ecosystem structure, function, and future trajectory. The problem can be stated in a more prescriptive way: How do we mitigate the costly environmental effects of human settlement, land use, and urban development? Much of the demand for research information comes from individuals and organizations already acting to ameliorate these negative effects. Ecological restoration, urban forestry, and greenspace management are but a few of the international efforts begging not just for more technical knowledge but for a comprehensive and integrated approach that fully accounts for the spatial and temporal distribution of benefits and costs of different actions. The rationale for developing an ecological science and management policy for urban forestry is simple. Nature and society operate as systems. Any action will affect the operation of the whole system; and various system states, or modes of operation, generate various spatial-temporal distributions of benefits and costs.

During the last two decades, urban forestry took its first steps in employing ecological concepts and methods, thus putting the discipline on sound, but preliminary, scientific footing. Scientists, teachers, and managers in urban forestry are being asked to take the next step and formulate their future in terms of ecosystem management by incorporating expanded time and space horizons, accounting for externalities, and monitoring fluxes of energy, water, and matter within and between adjacent and proximate ecosystems. Is urban forestry ready for ecosystem management? To answer this we need to examine how the core and context are informing each other. From this examination, we can determine if the scientific core is evolving in conjunction and synchrony with its management context.

The Core of Urban Forest Ecology

As a new field of study and practice emerges, concepts and methods are either borrowed or invented. Those who have participated in the construction of the core of knowledge in urban forest ecology wisely have avoided making up new concepts that would create a narrow and somewhat exclusive vocabulary. The task has been to import and test concepts from forest ecology to see if they are useful in establishing a scientific foundation for urban forest ecology. The fundamental concepts of structure and function are traditionally used in examining any system, from cell to landscape, and have served forest ecology well. Thus there was little difficulty in importing and successfully using them in urban forest ecology. More difficult is the search for means to describe how the parts make up the whole.

Structure and Function

Structure is the array of static attributes of the urban forest, the concept that asks the question “What is where?” *Function* is the dynamic operation of the forest: how the vegetation interacts with other components of the urban forest ecosystem, including humans, and how internal and external forces change urban forest structure over time. Examples of structure are the spatial distribution of species, biomass, size, age, and condition classes—the attributes one would record in an inventory of all the trees in a city. A slightly expanded definition of structure—one that would move our thinking toward the concept of the urban forest ecosystem—would include other attributes determining the condition of trees, plants, and soils. For example, just as the size and spatial distribution of rock outcrops are part of what determines the structure and function of mountain forests, the spatial patterns of buildings and other artificial surfaces define the geography of growing space for urban trees and plants and determine many of the conditions under which they will live.

Examples of function are the physiological operations sustaining life in the vegetation and soil and how these operations affect other components of the urban forest ecosystem, including people. Trees transpire and create a moist microenvironment for insects while cooling the air for humans. Roots break sidewalks in their search for nutrients, water, and gas exchange. Shade allows people to turn down their air-conditioners. When a tree affects something else in the system, or vice versa, that is ecological function. The functions of disease and aging change forest composition over time. The functional interactions with weather and humans provide for episodic changes like fires and ice storms. Inherent in the ecological approach, and the foundation for ecosystem management, is the capacity to understand structure and function at different spatial and temporal scales and to incorporate both gradual and episodic (often termed “catastrophic”) changes.

At the smallest scale, the ecological functioning of the urban forest begins with the interactions between individual trees and with other components of the ecosystem. When thinking about structure and function at different scales, one asks how activities at one scale influence those at another. How, for example, does the operation of a single tree fit into the functioning of the forest ecosystem? Answering this question incorporates the study of arboriculture into urban forest ecology. Therefore, sound ecological thinking integrates the operations of individual trees with the functioning of groups of trees, or stands, at the scale of the yard, block, neighborhood, planning district, census tract, city forest, urbanized area forest (including built-up areas outside the city limits), and the region. It’s axiomatic that activities at each spatial and temporal scale influence the scales above and below them. Fitting the urban forest ecosystem into this scheme requires, first, a brief discussion of entities and boundaries.

Boundaries, Gradients, and Linkages

We use boundaries to define entities. An attribute of urban forest structure is its spatial extent. Thus a basic question is “Where is the urban forest’s boundary with nonurban vegetation?” This raises allied questions about integrating our understanding of the structure and function of urban, periurban, and exurban forests. Urban forest boundaries can be defined in several ways, such as the political boundaries of the city, the “urbanized area,” and the Standard Metropolitan Statistical Area (SMSA). These political, jurisdictional, or morphological criteria can be part of a definition of the urban forest if we augment them with biological or ecological considerations. For example, one attribute of structure distinguishing the urban forest from the wildland forest is the absence of a fully articulated understory. A functional difference is found in the truncated nutrient cycles of the urban forest where people import fertilizers and export fallen leaves.

Undeveloped areas within the city limits or the urbanized areas or the SMSAs may appear, in both structure and function, to be nonurban forests or stands. These woods may have fully articulated vertical stratification, unbroken biochemical cycles, and other structural and functional attributes similar to nonurban forest stands. However, one perspective is that while there is little visible evidence of human influence in these stands, their current and future status is governed entirely by invisible but powerful human processes of land speculation, regulation, taxation, and development. Therefore, their existence is wholly determined by socioeconomic processes based in the general and local urban culture.

Following this line of reasoning raises the question “Aren’t all forests whose structure and / or function are predominantly governed by urban-based processes—visible or invisible—to be considered urban forests?” Forests whose current and future structure and function are determined principally by urban forces are certainly different from forests evolving under nonurban conditions. Further development of this line of reasoning leads to (1) a semantic discussion that could easily become preoccupied with what is and what is not urban; (2) the notion that forest science and policy of the future, at least in urbanizing states, will draw more and more upon the accumulated knowledge and wisdom of what is now called urban forestry; or (3) the need for an overarching concept that does not rely on distinctions between urban and nonurban for its efficacy. I will pursue the third alternative in the next section.

As preparation for an elaboration of that concept, visualize the urban forest as part of a mosaic of functionally connected vegetation systems laid out across the landscape like a patchwork quilt. The borders of quilt patches are discrete. On nonurban landscapes, the edges of the pieces in the mosaic are often "fuzzy," more like gradients than discrete boundaries. Urban activities commonly impose discrete boundaries, but there are increasingly cases where the edge of the urban forest is hard to distinguish from that of the surrounding wildland landscape. An example is found along a transect from a city to the dispersed settlement of exurban areas. The gradient of urbanization may occur sharply in some places and more gradually in others. The form, or morphology, of the gradient determines the behavior of functional processes linking urban, periurban, and exurban zones along the gradient. For example, Zembal (1993) found that the endangered lightfooted clapper rail, a bird found in periurban coastal marshes, decreased in numbers when certain patterns of land use intervened to prevent coyotes from preying on introduced foxes and cats, predators of the rail. In addition to wildlife connections, we are beginning to understand energy, water, and nutrient fluxes among urban, periurban, and exurban segments of the landscape gradient.

The innovative work of Pouyat, McDonnell, and Pickett (in press) and others at the Institute for Ecosystem Studies (Millbrook, New York) has helped scientists free themselves of the constraints of viewing the urban forest in jurisdictional or Census Bureau terms by suggesting that we use an "urban-to-rural gradient" of land use intensity to explain the continuum of vegetation change from city to country. Bradley has recently updated a model for understanding the sequence of land uses along this gradient in a way that illuminates the relationship between the hierarchy of urban-influenced uses and vegetation structures that will occur along the gradient (Bradley 1984; Bradley and Bare 1993).

Needed: A Systems Approach Embracing Multiple Scales of Space and Time

There is a need for a systems-oriented approach to guide the core and context of urban forest ecology into the future. This need is nurtured by modern changes in the urbanization process and resulting settlement patterns. It is nurtured also by changes in the kinds of questions being asked of scientists and managers. The ease of telecommunicating with modems and faxes encourages more dispersed settlement in high-amenity exurban wildlands. A portion of the western slope of the Sierra Nevada lies just to the east of Sacramento, California. This area is being populated by people with urban values, urban-generated equity, and urban histories. They have socioeconomic links with the Sacramento urban area. There are biophysical links as well. The structure of the Sacramento urban forest determines how much automobile-emitted air pollution will migrate on the easterly flow of air to the forests surrounding these homes on the west slope of the Sierra. This air pollution can make a critical difference to Sierra forest health. Conversely, the health of the Sierra forests directly affects the people in the Sacramento urban forest. A recent forest fire in the Sierra forests disrupted the water supply and damaged electric-generating capabilities. All of this has an impact on what is done in the Sacramento urban forest. Reduced hydroelectric-generating capacity in the Sierra increases the need for planting energy-saving trees in Sacramento.

Another example points up the need to have a systems approach that can link biophysical and socioeconomic relationships across long distances in a meaningful way. McPherson (1991) calculated that 17 percent of the water requirements of a yard tree planted to reduce a householder's air-conditioning energy use was saved by reducing the power plant's cooling water use. If we can account for changes in the flux of energy, pollution, and water across ecosystem boundaries, as in these examples, we will have a truer accounting of the spatial distribution of benefits and costs resulting from changes in urban forest structures and functions.

Because of the way urban forests are linked by a large number of biophysical and human processes to periurban and exurban forests, we need a concept that can take urban forestry forward in both science and management. The ecosystem concept allows the urban forester to see structural and functional characteristics inside the urban forest in relation to characteristics in adjacent vegetation systems. This helps, for example, in understanding the ecological consequences of a city's expansion into undeveloped wildlands, or of urban exotics escaping into native forest stands. We now look at how the ecosystem concept is beginning to dominate the policy-management context for urban forest ecology, today, and what attributes of the concept may govern the future evolution of both core and context of urban forest ecology.

Renaissance for the Ecosystem Concept

The year 1995 will mark the sixtieth anniversary of the publication of A.G. Tansley's classic paper advancing the notion that "it is the [eco]systems so formed which . . . are the basic units of nature on the face of the earth" (Tansley 1935:299). (Readers interested in the development of the ecosystem concept are referred primarily to Golley 1993, with examples of important papers available in Real and Brown 1991.) It took more than thirty years before a full articulation of the ecosystem concept in natural resource management was published by leading ecologists and resource scientists (Van Dyne 1969). Another quarter century had to pass before federal and state land management agencies adopted ecosystem management as policy. This was as bold and challenging a step as the introduction of Pinchot's "multiple use" concept of the early 1900s. (For a concise review of the early history of forest ecosystem policy, see Caldwell 1970.) The new philosophy requires that the public and private sectors join to plan and manage ecosystems that cross jurisdictional boundaries and comprise multiple ownerships, thus it is particularly important as context for urban forestry. The policy emphasizes that the ecological behavior and condition of these lands will be determined by the coordinated effort of private and public land planners and managers.

State land agencies together with other federal agencies also are adopting ecosystem management as their guiding policy. This is a major shift for land planning and urban forestry over a relatively short time. Because of the rapidity of contextual change, the new approach has its detractors, especially concerning the potential for constraints on private property. Nevertheless, federal and state agencies are adopting the policy, and professional organizations like the Society of American Foresters and the Ecological Society of America are forging their own interpretations of what ecosystem management means. In several cases, urban-based organizations are one to two years into an examination of how they can use and implement this policy for urban forestry. Because the U.S. Forest Service provides most of the funds for urban forestry research and application, we shall examine more closely this organization's articulation of ecosystem management inasmuch as it has become the context in which we do our science and think about urban forest planning and management.

Ecosystem Management as Context for Urban Forest Science and Practice

In February 1994, the Chief of the U.S. Forest Service described the main orientation of ecosystem management as a land policy (USDA Forest Service 1994a): "Ecosystem management is a holistic approach to natural resource management, moving beyond a compartmentalized approach focusing on individual parts of the forest. It's an approach that steps back from the forest stand and focuses on the forest landscape and its position in the larger environment in order to integrate the human, biological, and physical dimensions of natural resource management. The purpose is to achieve sustainability of all resources." Applied to urban forest ecology, this would suggest that we stop viewing urban, periurban, and exurban forests as separate compartments and focus on what connects these systems and how actions in one system affect the operation of the systems linked to it.

In most statements about ecosystem management, Forest Service policy makers have stressed that it is a science-based approach to land management. Thus it is pertinent to our discussion to read how the research branch of this agency has responded to the new policy. This research policy statement sharpens the focus of the evolution and development of urban forest ecology's core and context. The Forest Service Research (FSR) Strategic Plan for the 1990s (USDA Forest Service 1992) defines three high priority research problems that are closely related to the work urban forest scientists do. The headings are taken from the FSR Strategic Plan. I have added comments relating the Plan to urban forest ecology's core and context.

1. *Understanding Ecosystems.* The FSR plan seeks to understand the basic structure and function of ecosystems. Urban forest ecology examines the human-induced attributes of ecosystems, specifically the results of human land use changes, especially those occurring when land is developed and used for residential, commercial, and industrial purposes.
2. *Understanding People and Natural Resource Relationships*. If we are to grasp the ecological changes resulting from shifts in land use, and inform land managers how to anticipate and mitigate them, our research should understand those forces motivating spatial and temporal migrations of land uses. This type of demographic, cultural, and sociological information is required if we are to predict where future uses will occur and what they will do to the land. In order to assign values (benefits or costs) to alternative ecosystem and/or landscape vegetation structures, we will have to understand what drives those values and how they are best expressed, quantitatively and qualitatively, for different groups of people.
3. *Understanding and Expanding Resource Options*. The ecosystem management policy implies very strongly that resource options should be preserved for future generations. To do that requires scientists and managers to employ an ecological accounting system that describes who will benefit and who will pay, when and where, for a given resource decision. Ecosystem management is an accounting system that links resource systems in space and in time.

How Does Urban Forest Science Respond?

For the scientific core and policy context to be efficiently integrated, they must inform one another. Articulation of the general ecosystem management policy followed by the specific ecosystem management research policy is context informing core. How can science respond in order to inform land management? First, it has to identify the central question that will drive the research and advice to management.

That central question can be stated as "How do, and how should, vegetation-soil complexes (and associated biophysical attributes of the ecosystem) change as people settle and urbanize the land?" Or, "How do various land uses, manifested in various spatial-temporal patterns, change forest vegetation and soils at different scales of inquiry?" And "How do these patterns translate into benefits and costs?" Part of the problem is we do not fully understand how to develop information about these altered ecosystems, or parts of them, that can be utilized up and down the interscalar ladder. For example, we can examine how effective a tree's shade is in reducing the need for air-conditioning in a house. Up the spatial scale, we can model a neighborhood or town tree-planting program to increase the magnitude of these savings. Further up the spatial scale, we can design a tree-planting plan for an electric utility's service area that comprises hundreds of such towns. But, this proposed increase in tree density will have unknown effects on micro, meso, and macro climates, as it will on regional water, carbon, and hydrocarbon budgets and on regional air quality. There will be some good effects, some bad effects. So, just as we inquired up the ladder of spatial scales we must inquire up the ladder of temporal scales to see who will bear the costs and who will reap the benefits over time. Perhaps, in this example, the current generation of householders will bear the cost of planting, a second generation will reap the benefits of lower energy bills, and their children's generation will bear the cost of removing a large population of aging trees.

Research must begin by designing studies along three dimensions: (1) from small to large spatial scales, (2) from small to large temporal scales, and (3) from low to high levels of ecosystem disturbance from land uses. The third can be described by experimental sites or domains along a gradient from low to high modification of presettlement ecosystem structure. This can be called the "urban-to-rural land use gradient," though it does not always occur in space as a smooth continuum from city to country. The experimental domains are defined by their land use attributes, such as dense commercial, sparse residential, or transportation corridor. It is at this point that the types of land use have to be limited to focus the research. For example, urban forest ecology should not include wildland recreational use of a nonresidential character (e.g., hiking, camping). Yet the study of how a second-home residential, commercial, and recreational community set in a mountain forest ecosystem is changing the functional role of vegetation and soils takes advantage of the core skills of urban forest ecologists.

If research is conducted at different spatial and temporal scales, it will illuminate the linkages between knowledge at one scale and knowledge at another. This will also reveal the links between the various experimental domains along the gradient of ecosystem modification. For example, learning that increasing the density of tree cover in an urban center loads ozone precursors (volatile hydrocarbons) on downwind forests (near the rural or unmodified end of the gradient) helps us understand the elusive relations that impart a benefit to one domain (in this case the urban center) and a cost to another.

This approach can result in a nested set of studies from smaller to larger spatial and temporal scales. "Nested" means that the studies are designed, often concurrently, so that results generated at one scale can be evaluated for use at smaller and larger scales. This interscalar approach is also helpful in building decision support models that will address the scale of, for example, the homeowner who wants to steward his or her trees through a season of drought (a small spatial-temporal scale) to an interagency council wanting to know what the cumulative effects of private land development in eleven counties will be twenty-five years from now. In evaluating how interscalar information is used, scientists will pay particular attention to two inherent problems: (1) the expansion of error as small-scale information is "blown up" to larger scales; (2) different variables becoming important at different scales, making it difficult to assume that processes operating at one scale operate similarly at another.

What follows is an example of how the questions discussed above can be restated so as to organize studies into two groups. In practice, however, a single study can address both of the following questions:

1. *How has presettlement forest structure and function changed as a result of different settlement patterns*? This work can be conducted at three spatial scales of inquiry—the community, the county, and the multicounty region. There are various temporal scales, but the intent is to speak to the problem of long-term, cumulative effects of settlement, tree removal, soil disturbance, and revegetation, including tree planting. Presettlement, and preurban, forest structure is a baseline condition against which changes can be measured and value judgments made. The scales are described below in terms of political units, but the ecosystem approach precludes drawing discrete boundaries around political or jurisdictional areas. In the measurement of both structure and function, the researcher can include adjacent and surrounding areas by looking one level up the scale.

   Community Scale. Presettlement forest structure can be documented from historical sources for communities in different forest types (McBride and Jacobs 1975, 1986). Contemporary forest structure and function are specified and compared to presettlement structure to learn how community land uses have changed the ecosystem. For example, research in the upper montane Sierra forest type at the community of Bear Valley, California, uses an undeveloped forest nearby as the presettlement “control” forest. The road network and water supply reservoir in Bear Valley have modified the natural distribution of water for meadow and tree growth. A prohibition against tree removal works together with these changes in water distribution to change the trajectory of forest succession from that occurring on the control plot (McBride and Rowntree, in preparation). This study is developing a benefit-cost array that will support a forest management plan for Bear Valley that utilizes knowledge about these changes. (The community wishes to arrest succession and manage for early- to middle-seral plant associations.) It is being determined how representative Bear Valley is of all upper montane Sierra communities and to what degree these results can be extrapolated throughout that forest type. In other regions of the country, community scale studies can, for example, examine how exotic tree species (such as Norway maple) compete with, and replace, natives (such as sugar maple), and how imported natives might change the genetic architecture of a local native population of trees.

County Scale. County general plans specify where residential and commercial land uses can occur and at what densities. An example of research at this scale is to take a county plan and determine what changes will occur to forest and ecosystem structure and function as the general plan is implemented. This determination considers both tree removals and tree plantings that, among other things, bear on natural regeneration, or lack of it, and the mixing of native and exotic species and genetic material. Future projections are augmented by an analysis documenting historically the cumulative effects of land use change to the present. Work at this scale feeds immediately into regional scale research (Zipperer 1993). Once these structural scenarios are complete, studies under question 2, below, can examine changes to function, such as modified countywide water, carbon, and pollutant fluxes.

Regional Scale. Here, information from community and county scales is aggregated upward in spatial scale to a region of about three to eleven counties attempting to discern large-scale patterns in land use induced changes. Often, the region under study contains both developed and undeveloped land, and there is a range of land use/vegetation mixtures. At the regional spatial scale, results are often expressed at large temporal scales. For example, a seven-county study of future impacts of residential and commercial land use change employs county general plans as the data base for constructing a twenty-five year “build-out scenario” that is superimposed on the existing vegetation map for the seven-county area. This describes what vegetation changes would occur if building proceeds according to the counties’ general plans (Rowntree et al. 1993). The results form the basis for calculating loss of wildlife habitat, changes in visual and recreational quality, and (see question 2 below) changes in regional water, energy, and pollutant patterns.

2. *How have fluxes or flows of energy, water, and pollutants changed with land use induced changes in forest structure and function*? These studies also should be conducted at several spatial scales and seek to understand modified fluxes into, through, and out of the ecosystem or landscape when land use modifies vegetation and soil structure.

Site Scale. Research in urban forest ecology has, for a number of years, measured changes in energy flux resulting from changes in vegetation, particularly as these relate to human benefits and costs, such as studies measuring energy savings to a homeowner from the reconfiguration of trees and landscape plants around the residence to form windbreaks and shade trees (Heisler 1986, 1990). Associated changes in water utilization can be calculated for any changes in vegetation configuration that may save energy, and the two are combined to estimate a net savings or cost. Basic research at the site scale seeks to understand the flux of incoming solar radiation as it bears on winter solar heating potential (e.g., amounts of winter sun transmission through the crowns of different species), human thermal comfort or stress, and human exposure to the ultraviolet (UV) portion of the light spectrum (Yang et al., in press).

Other flux studies at the site scale link the interaction of energy and water, such as ambient air cooling potential of trees and ground cover in various configurations. Together with the shading potential of trees, evapotranspiration (ET) cooling has the potential for reducing air-conditioning energy use. However, to engage in ET a tree must have access to soil water, and in urban areas soils are often dry due to rainfall runoff from impervious surfaces or too compacted to hold and deliver sufficient water for effective ET cooling. Thus our research must understand the interaction of these factors (Simpson 1993). In addition, there is potentially a wide range of "pumping rates" among the species used for residential and commercial planting. Rates at which different natives and cultivars use water, intercept and transmit solar radiation, produce volatile hydrocarbons, absorb noxious gases, and collect airborne particulates should be examined at the site scale to establish basic flux relations, then extrapolated to larger spatial scales.

Parking lots are important site-scale research locales. Without trees they become urban heat islands, produce high amounts of polluted runoff, and are places where people bear high heat and UV loads. Trees modify the energy and water fluxes so that there is less heat and UV stress on people, less heat is advected (horizontally) to adjacent sites, and less energy and gas (and less air pollution) are used to cool automobile interiors. Research at the site scale can refine these facts, establish relationships, quantify benefits and costs, and form the basis for aggregation to larger spatial scales.

Community Scale. Because towns and cities are political jurisdictions, this scale is useful in providing certain types of planning and management information dealing with energy, water, and pollutant flux. Other kinds of information are better passed to managers at the county or regional scale. Some scientific questions are more effectively addressed by adding a scale between site and community, such as "neighborhood." For example, Simpson (1993) seeks to answer the question "What is the minimum area of trees, at high urban densities, required to achieve measurable ET cooling?" This requires testing at several scales ranging from site to community. Similarly, Nowak (1994a, b) employs measurements of urban forest leaf area at different scales to estimate the quantity of pollutants removed from the atmosphere.

Scientists can develop a typology of experimental sites along the urban-to-rural gradient, such as high density urban commercial areas, parking lots, quarter acre single-family residential communities, and freeway interchanges. For each type, the range of fluxes for water, energy, and pollutants can be established from empirical measurements and simulation studies that rely on inherent site attributes as well as on the way the site is linked to adjacent sites.

County and Regional Scales. Models of water, energy, and pollutant flux can be constructed at the county and regional scales based on relations established at the site and community scales. At the regional scale, we can begin to see interactions between large urbanizing areas and adjacent forested areas. For example, three of the major urbanizing regions in the West—the Colorado Front, the Salt Lake Valley, and the Sacramento-San Joaquin Valley—are adjacent to major forested mountain ranges, and the urban air pollution affects vegetation, soils, and runoff quality in the mountains. Because these cities rely on mountain runoff for water, air pollutants can theoretically be returned to the cities in the water. This is an example of how accounting for fluxes between two ecosystems can illuminate the role of the urban forest. Research can now begin to model the fraction of gaseous and particulate air pollution removed from the airstream by various densities and configurations of urban vegetation in both present and future urbanized areas. This will estimate reductions in future air pollution loads on adjacent mountain forest lands. The model can also estimate the production of ozone precursors (volatile hydrocarbons) by the urban vegetation, water use and the effects of runoff, energy use, and carbon sequestering and storage.

Difficulties with the Ecosystem Concept

Whether it is used in core scientific studies or in the policy and management context, the ecosystem concept is not without its problems. For natural systems, some of these difficulties are minimized. For modified systems where humans are rearranging structure and function, some of these difficulties are exacerbated. The following discussion includes, but is not limited to, problems that confront urban forest ecologists.

Where Do Humans Fit In?

There are few ecosystems today that haven't been modified, directly or indirectly, by humans. However, a question that comes up early in any discussion about applying the ecosystem concept to human-modified landscapes is "How does one accommodate the activity of humans in a model of structure, function, and flux?" A corollary is "Are humans internal or external to the ecosystem?" (USDA Forest Service 1994b). They can be viewed usefully as both internal and external components. That is, humans are tool-using "megafauna" operating within an ecosystem, albeit with more consequence than other fauna. They rearrange the flux of energy, water, and matter. (In smaller amounts, so does a hummingbird.) In the Sierra Nevada Ecosystem Project (SNEP), analysis proceeds on the assumption that ecosystems are being modified by humans internal to Sierran ecosystems, but also as forces producing fluxes into those systems from outside (SNEP 1994).

The point is that ecosystem theory and ecosystem science easily accommodate human activity. In fact, the usefulness of the ecosystem concept to human society may be largely in the area of understanding and guiding interactions between humans and nature. Ecosystem theory incorporates feedback loops, and these can be used to clarify human-ecosystem interaction. For example, humans perceive a given ecosystem state. They evaluate it in relation to their needs and usually make changes. They watch how these changes affect system properties and processes and evaluate the new system state. Further changes are made, and so on. The feedback of human evaluation and modifications into the sequence of ecosystem states either amplifies or dampens the degree to which an ecosystem's trajectory will vary from what would have occurred naturally.

Complexity

Reality is complex, and the ecosystem concept is a mental construct that attempts to model the real world. When it does fairly well at that, it approaches a complexity that may frustrate its use in science and / or management. The ecosystem concept requires a high level of scientific participation if it is to reach its potential. Can the core of urban forest ecology participate at the required level? As a science, urban forest ecology is just beginning to deal with complex systems.

For example, scientists and practitioners have long believed that adding trees will make a city cooler. Tree-planting programs and demonstration projects have been based on this idea. Evapotranspiration (ET) cooling is one of the oldest hypotheses in urban cumatology, yet the scientific information is inadequate to indicate how many degrees reduction in average air temperature will occur with an addition of a number of trees in any given pattern (Simpson 1993). The physics of evapotranspiration and heat transfer suggest that the relationship is based on sound theory. If so, why don't we have a more precise understanding of the relationship?

First, the relationship, like so many aspects of urban forest ecology, is more complex than it seems. There is great variation in the rate that different species transpire water. Many urban trees have too little water and too much radiation, and consequently close up their stomata and don't transpire for much of the day. An excessive density of trees restricts airflow, and heat and moisture build up in and below the canopy. Years ago, it was sufficient to assume there was roughly a linear relationship: more trees equals a cooler city. This assumption adequately supported tree-planting programs. Today, however, cities and electric utilities demand a more precise relationship. How many trees in what configuration will bring down temperatures by how much over how large an area? The more precise relationship is required for benefit-cost analyses, yet it will be years before scientists can produce these numbers for planners and managers.

A similar problem may develop in the context of ecosystem management. At first, the idea is attractive, but we don't appreciate the information and knowledge requirements of implementing it. As time passes, urban forest management becomes committed to it, but scientists cannot participate at the level required to make ecosystem analysis and management work. At the outset of this chapter, it was stated that we have to understand how the core and context of urban forest ecology inform and support one another. For ecosystem management to work—given its inherent complexity—there has to be (1) improved communication between scientists and managers (i.e., core and context need to efficiently inform one another), and (2) a realistic ratio between program and science funding.

Program funds nurture the activities of urban forestry which in turn create the demand level for scientific information. Over the last fifteen years, the ratio between Forest Service program funds (administered to the states by the State and Private Forestry branch of the agency) and funds dedicated to urban forest research has been in a range between 10:1 and 20:1 (program to research). As urban forest ecology shifts to a higher plane of scientific expectation in the context of ecosystem management, the ratio will have to change in order to reduce the disparity between demand for knowledge and the scientific core's ability to provide it.

Uncertainty

Uncertainty in ecosystem management might be described as the disparity between what we know and what we believe we should know about how these systems work. Because the ecosystem concept is a more complete representation of reality than previous mental constructs, one feels closer to the truth. But, because it is difficult to meet the information demands of this more complex view of the world, there will be more uncertainty. Thus scientists and managers move from one kind of uncertainty—where our models were imperfect representations of reality—to another, where our models are more complete, but we haven't the information power to document and run them with confidence.

According to Frank Golley, ecologist and historian of the ecosystem concept, some scientists have charged that the concept is too deterministic, giving the false impression that we can control these systems (Golley 1993:190). These critics say that deterministic cause-and-effect models do not take into consideration the inherent chaos in nature, particularly in disturbed systems. This charge is important to our discussion because urban forest ecosystems are disturbed ecosystems. Golley agrees with these critics that disturbed ecosystems tend to be more chaotic, but he makes the error of lumping natural and human disturbances together (p. 197). There is an important distinction that is particularly relevant to urban forest ecology.

Human-disturbed ecosystems, including urban forest ecosystems, may be less chaotic than many natural-disturbed systems because of the relatively predictable behavior of human institutions compared to natural disturbances. Of course, natural systems into which humans have just begun to intervene can become quite unpredictable and chaotic because of the many yet unknown interactions between human and natural processes. In established urban forest ecosystems, however, the human hand is much more dominant, and thus control over fluctuations is greater. Internally, chaos and uncertainty are less of an issue than in natural systems. It is externally, where urban forest ecosystems are linked with natural ecosystems (particularly those functioning under one or more disturbance regimes), that there is a high potential for chaos and uncertainty.

Multiple Ownerships

Because ecosystems include more than one landowner or manager, a challenge for ecosystem management is having all landowners understand and accept the concept. This issue is of particular interest to urban forestry professionals. Lynton Caldwell, a senior scholar of land and forest policy, advocated an ecosystem approach to land management twenty-five years ago, stating: "the natural processes of physical and biological systems that comprise the land do not necessarily accommodate themselves to the artificial boundaries and restrictions that law and political economy impose upon them" (Caldwell 1970:203). There seems to be no disagreement that parts of a system must be coordinated in order for that system to run efficiently and accomplish its objective.

Federal and state plans to implement ecosystem management respect private property rights. Yet the trend over the last century has been to gradually curtail private property rights as society has learned how the environment works and about the importance of property owners' cooperating for the common good. We are still on the steep part of the learning curve regarding how our individual activities affect the ecosystem in which we live and the ecosystems to which ours is coupled. Thus the challenge is in education rather than regulation. This places even more responsibility on scientists to explain what ecosystems are, how they work, and how landownership and land management affect their structure, function, and long-term trajectory.

Members of the urban forestry community will be interested in how this effort proceeds, because they have been involved for years in educating homeowners and commercial property owners toward a better understanding of how their individual properties contribute to the urban forest ecosystem. Without a doubt, this is another critical topic on which the core and context of urban forest ecology need to inform one another.

Conclusion: Science and Context

The core and context of urban forest ecology can take the first steps toward ecosystem management by boiling the concept down to a fundamental principle on which scientists and managers can focus. It will not be new, for it has been part of conventional wisdom in land management, indeed in our view of the world, for years. It is that everything is related, and nothing changes without having consequences throughout the system and adjoining systems. The task is to understand and account for these changes. Theoretically, ecosystem management must account for all changes, with each change given a human value—a magnitude of benefit or cost expressed quantitatively or qualitatively. While this may be difficult if not impossible for a while, ecosystem management makes explicit the responsibility for scientist and manager to make as full an accounting as possible. Thus the ecosystem concept infuses into both the core and context of our field not only a better representation of reality but a higher level of responsibility.

During this paradigm shift, I am optimistic about the core and context of urban forest ecology advancing in a mutually beneficial manner. The basis for this optimism is exemplified by a course developed in 1993 by a group of urban forest ecologists—planners, managers, and scientists. Entitled "An Ecosystem Approach to Urban and Community Forestry" (USDA Forest Service 1993), this week-long workshop was tested in several cities in the Midwest and East, where the students ranged across the spectrum of urban forestry professionals. The Urban Forestry Center of the University of Pennsylvania's Morris Arboretum conducted an evaluation of the course and concluded that it successfully conveyed ecosystem principles and management strategies for urban forestry (R.L. Neville, USDA Forest Service, Syracuse, New York, pers. comm., 1994). The course is being fine-tuned for a second round of offerings in 1994–95.

Kai Lee begins the preface of his recent book, *Compass and Gyroscope*, with the observation that "civilized life cannot continue in its present form" (Lee 1993). The sheer number of people, combined with our powerful technologies, guarantees that we will alter the planet on which we must continue to evolve. *Homo sapiens* is trying to adjust quickly to changing ecosystems we don't understand. The peril lies in our fear of complexity and our desire to have science tell us what to do. Kai argues that the response to that fear is in an approach called "adaptive management" where the best science, albeit incomplete, is brought to bear on an ecosystem, management is implemented under rigorously monitored conditions, and adaptations in management are made as the feedback from monitoring teaches us more about the way the ecosystem behaves. Adaptive management is being tested in rural ecosystems, such as the Hayfork Adaptive Management Area in northern California, which is part of the implementation of the Forest Ecosystem Management Assessment Team's study of the northern spotted owl region.

Adaptive management areas for urban forest ecosystems must be established soon, for it is this approach that will test the ability of scientists and managers to cooperate in apprehending these complex systems. (See McPherson 1993 for a discussion of urban forest ecosystem monitoring.) This cooperation can be enhanced if there is a conjunction of meaning and purpose founded on common vocabulary and concepts. And this conjunction will occur if the two domains of urban forest ecology—scientific core and policy context—can continue to inform one another as they shift and evolve.

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