Ecosystems (2001) 4: 782–796
DOI: 10.1007/s10021-001-0046-8

ECOSYSTEMS

ORIGINAL ARTICLES

The Urban Funnel Model and the Spatially Heterogeneous Ecological Footprint

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ABSTRACT

Urban ecological systems are characterized by complex interactions between the natural environment and humans at multiple scales; for an individual urban ecosystem, the strongest interactions may occur at the local or regional spatial scale. At the regional scale, external ecosystems produce resources that are acquired and transported by humans to urban areas, where they are processed and consumed. The assimilation of diffuse human wastes and pollutants also occurs at the regional scale, with much of this process occurring external to the urban system. We developed the urban funnel model to conceptualize the integration of humans into their ecological context. The model captures this pattern and process of resource appropriation and waste generation by urban ecosystems at various spatial scales. This model is applied to individual cities using a modification of traditional ecological footprint (EF) analysis that is spatially explicit; the incorporation of spatial heterogeneity in calculating the EF greatly improves its accuracy. The method for EF analysis can be further modified to ensure that a certain proportion of potential ecosystem services are left for in situ processes. Combining EF models of human appropriation with ecosystem process models would help us to learn more about the effects of ecosystem service appropriation. By comparing the results for food and water, we were able to identify some of the potentially limiting ecological factors for cities. A comparison of the EFs for the 20 largest US cities showed the importance of urban location and interurban competition for ecosystem services. This study underscores the need to take multiple scales and spatial heterogeneity into consideration to expand our current understanding of human–ecosystem interactions. The urban funnel model and the spatially heterogeneous EF provide an effective means of achieving this goal.

Key words: urban funnel model; human–ecosystem interaction; spatially heterogeneous ecological footprint; scale of resource appropriation; water; food; carbon assimilation.

INTRODUCTION

To understand how urban ecosystems work, we need to consider the interactions between social and ecological processes. Human systems depend on ecosystem services (Costanza and others 1997; Daily 1997), but human activities can alter the ability of ecosystems to produce these services. Human activities affect ecosystems through multiple mechanisms, including the direct alteration of biogeochemical cycles, species assemblages, and terrestrial land-cover characteristics (Vitousek 1994). For example, increases in atmospheric carbon and bio-

Received 17 October 2000; accepted 31 May 2001.
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available nitrogen can affect primary productivity, nutrient retention capabilities, and global climate; deliberate and accidental introductions of nonnative species alter regional biogeographical patterns; and direct land-cover transformations such as urbanization and agricultural conversion, as well as induced land-cover changes such as desertification, greatly modify the patterns and processes of existing ecosystems. As a result of these changes, humans have now appropriated as much as 40% of terrestrial potential net primary productivity (NPP) (Vitousek and others 1986; Haberl 1997), 26% of terrestrial evapotranspiration, and 54% of runoff (Postel and others 1996) on a global scale. Any synthetic universe that purports to represent the ecosystem processes occurring in human-dominated landscapes must therefore explicitly incorporate human activities.

The city is the principal socioeconomic entity that provides for human habitation; current estimates indicate that over half of the global population will soon live in urban centers (UN 1997). The US Census Bureau (1995) has defined *urban areas* as places having 2500 or more residents and *urbanized areas* as places inhabited by at least 50,000 people, including the *urban fringe*, which is defined as having a population density of 2590 people per square kilometer (1000 people per square mile), although various other defining variables may also be appropriate (McIntyre and others 2001). Along with their high population density, cities are emergent structures that require a high degree of land modification, including the emplacement of impermeable materials (such as concrete, asphalt, and roofing materials) and the creation of an extensive infrastructure (sewage, water delivery, and transportation systems). They are centers of business and culture and have well-developed political, economic, and social organizations.

For the purposes of our study, we consider the urban ecosystem to be a city at a specific point in space that imports and consumes materials needed for human survival, such as food and water. At the same time, cities also are producers of other materials, including finished goods, services, technology, and information, and serve as the hubs of transportation networks. In the parlance of economics, cities are net producers; but in standard ecosystem terminology, cities are heterotrophic—that is, they cannot support total ecosystem metabolism by internal production alone—because their overall consumption of organic matter (ecosystem respiration, including that accounted for by burning fossil carbon) vastly exceeds the production of new organic matter by photosynthesis (Collins and others 2000). Production is much less than respiration in urban areas; they must therefore be net importers of materials. Although ecosystem services do exist within a city, including the reduction of noise and air pollution, the modification of local climate and runoff characteristics, and aesthetic and recreational benefits (Bolund and Hunhammar 1999), these services are not sufficient to sustain the urban system's material and respiratory demands or meet its need for waste assimilation. Moreover, the importance of these services is secondary to the basic requirements for human survival. Biological (or physiological) needs must be met first (Maslow 1954), and these needs cannot be fulfilled entirely by the city's internal ecosystem services.

As human history has evolved, our metabolic demands have expanded far beyond our basic biological requirements. The maintenance of the structure and function of advanced sociocultural systems and technology requires the throughput of energy typical of dissipative systems (Nicolis and Prigogine 1977). This additional consumption of external energy, termed "technometabolism" (Boyden and Dovers 1992), can be viewed as a positive feedback loop for the growth of human systems. As human technology and consumption increased, so did our ability to procure and consume resources from areas beyond our immediate surroundings. There is a long standing debate among archaeologists as to what events in human history triggered this shift; but whether it was spurred by the rise of agriculture or the advent of urbanization, it is now undeniable that the reach of human influence in the modern world extends to every corner of the globe (Redman 1999).

We distinguish urban ecosystems from rural ones, which are comprised of farms, agriculture, and other inhabited or intensively managed lands outside of cities, as well as wild lands—that is, regions that are not domesticated, cultivated, or tamed. Such nonurban areas are characterized by low human population density and less developed, more pervious surfaces; however, land modification by humans may still be high in rural systems. In contrast to urban systems, rural and wild-land ecosystems are often autotrophic; thus, they produce many of the resources required by cities. The ecosystems of the rural and wild lands that comprise the "hinterlands" of cities are thus appropriated to supply them with natural resources. Although these rural and wild lands are often physically distant from the urban areas that consume their resources, the degree to which they are manipulated and the extent of the land area that is exploited are determined by technology, economics, and the size, location, and demands of cities.

An examination of the ways in which a city interacts with rural and wild lands can provide insight into the human–ecosystem relationship. In contrast to wild-land ecosystems, ecosystems of concentrated human habitation are maintained through imports of materials and energy produced in external ecosystems. The appropriation is a dynamic process and is therefore independent of any single or particular ecosystem. Dependence on these external inputs frees human systems from ecological constraints occurring at the local scale, but in exchange it extends the impact of human influence to remote ecosystems.

The ecological footprint (EF) is the hypothetical area needed to provide the ecological services that a human or a city utilizes. It has been used to quantify the area from which ecosystem services are appropriated at local scales (Larsson and others 1994; Kautsky and others 1997) as well as regional or even global scales (Folke and others 1997, 1998; Young and others 1998; Jansson and others 1999). The EF concept also has been used as an indicator that measures the supply and demand of the renewable resources needed to ensure the sustainability of human systems (Wackernagel and Rees 1996; Wackernagel 1999). Because the Earth has a finite area, the sum of all EFs must be less than the planet's total area for the demands of the current population on ecosystem services to be sustainable. The area required to support a given system indefinitely cannot exceed the available productive area.

We developed a model to conceptualize the integration of specific urban areas with their reciprocal ecological processes at multiple scales and then used EF analysis to quantify these human-ecosystem interactions. To do so, we looked at the import of water, the production of food, and the absorption of emitted carbon dioxide for the Phoenix, Arizona, metropolitan area, a National Science Foundation urban Long-Term Ecological Research site, and then extended our analysis to the 20 largest US metropolitan areas. We hypothesized that city location would be an important factor. For example, although McDonnell and others (1997) showed that urban ecosystems were less productive than rural ecosystems in the eastern United States, we anticipated that the opposite would be true for Phoenix and for other cities that are embedded in harsh environments. This hypothesis was based on the observation that the import of water and nutrients to the city creates an "oasis" of high vegetation biomass in what would otherwise be an arid environment.

We examined several specific questions concerning the extent of influence of an urban ecosystem: (a) How does spatial heterogeneity in ecosystem services affect the EF? We expected that the nonrandom distribution of resources would increase or decrease the EF as a function of urban location. (b) How does the EF size differ for distinct ecological services? We hypothesized that because the rates at which ecosystem services are generated are specific for each service, the area appropriated for these services would be dependent on the resource. (c) How does the EF increase when the demand escalates for ecological services? We predicted that the EF size would increase nonlinearly in response to increases in ecosystem service requirements because the resources for their provision are not typically distributed uniformly across heterogeneous landscapes.

The Urban Funnel Model of Human–Ecological Integration

We need to devise new conceptual models that integrate multiple-scale social and ecological processes into a single integrated system (Loucks 1994; Pickett and others 1997). To be most effective, such a socioecological model would incorporate multiple-scale processes and feedback mechanisms simultaneously and would also explicitly identify the feedback mechanisms that integrate social and ecological processes. Although the effects of the social dynamics of human systems on the environment have been widely documented, we still need to identify the ecological processes that create ecological constraints on urban system or operate as feedback mechanisms.

In the last decade, a number of approaches have been developed to take the activities of humans into account as integral components of ecosystems; these include the urban–rural gradient (McDonnell and Pickett 1990; Pickett and others 1997), the watershed ecosystem approach (Pickett and others 1997), a landscape ecological approach (Pickett and others 1997; Numata 1998; Grimm and others 2000; Zipperer and others 2000), and a social ecological approach (Grove and Burch 1997). All of these approaches emphasize the interactions that occur internally or in close proximity to cities. However, reciprocal ecological interactions that affect land-use dynamics are often not identified at this scale because they are weak and difficult to detect. Because the strength of the interactions is not equal, there is a discontinuity in space between cities and the ecological systems that affect and are affected by them.

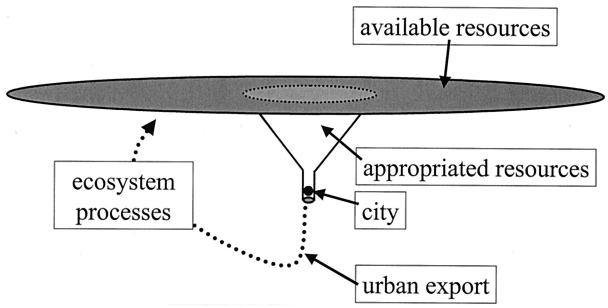

Figure 1. Schematic diagram of the urban funnel conceptual model. Resources are appropriated by a city from the pool of available resources, transported down the funnel to the city, and then processed and consumed. Excess materials and waste products are exported into the environment, where they may augment the pool of available resources.

Although a city directly regulates the environment within its boundaries, it is dependent on ecological services that exist at much larger scales and at substantial distances from the city. It is primarily the acquisition of external resources for human consumption, driven by socioeconomics, that allows human systems to grow and thrive. In order to relate local human dominance of feedback within the physical boundaries of urban areas with regional, human and ecological interactions, we developed a conceptual model to capture the multiple scales of these interactions, the urban funnel model (Figure 1).

The outermost ring at the top of the funnel taps into the entire pool of ecological resources and services that are available in the biosphere, a portion of which is appropriated by the city. The funnel represents the structure that channels the flow of materials imported by humans into the urban system. Each city has a funnel that competes for resources; none of the funnels is allowed to overlap with the funnel of another city competing for the identical resources. Technology, which influences the demand for resources and their transportation, affects the funnel size. The cone of the funnel represents the transportation network that concentrates and delivers the appropriated resources to the city. Within the urban domain, wastes are remedied (for example, the sewage treated in wastewater treatment plants), deposited and accumulated locally (for example, the solid waste dumped in landfills), or returned in a diffuse form to the biosphere (for example, emissions of gaseous and particulate atmospheric substances or the discharge of sewage effluent to receiving waters). These wastes may feed back to affect the pool of available biospheric resources positively (in the form of carbon and nitrogen accumulation or fertilization) or negatively (in the form of pollution).

Within the synthetic universe created by the funnel model, humans modify their effects on the environment primarily by regulating the rate at which they consume materials and the location from which their ecological services are drawn. Our model has allowed us to identify a new method that can describe the integration of human ecological processes at regional or continental scales; only at the scales from which ecological services are acquired are human practices expected to have ecological constraints. We use the EF to quantify the size of the top of the funnel, which represents the scale at which integrated socioecological interactions occur.

A Spatially Heterogeneous Ecological Footprint

EFs are usually computed by determining the per capita utilization of ecological services—for example, the consumption of water and food and the assimilation of emitted carbon dioxide—and then multiplying this figure by the population of interest and dividing it by the local average production potential of ecosystem services, to arrive at a measure of unit area, commonly hectares (Wackernagel and Rees 1996; Folke 1997):

$$\mathrm{EF} = \text{consumption [emission]} \times \text{population/mean production} \times \text{[assimilation]} \quad (1)$$

This method of calculating the EF is not without its critics; several papers arguing for and against the EF concept were presented in a recent forum organized by the journal *Ecological Economics* (2000; 32:341–94). It has been argued, for examples, that using a figure for mean ecosystem productivity as the basis for the calculation makes the unrealistic assumption that the production of ecosystem services is homogeneous. Therefore, to address this issue, we modified the method for quantifying the EF as follows: (a) We computed the EF separately for individual services instead of lumping all ecosystem services together, and (b) we calculated the EF in a spatially explicit manner, using the specific spatial data that pertained to each of the ecosystem services.

We investigated the effect of interurban competition and the influence of city location on the regional distribution of resources by comparing the EF sizes for cities both independently and then in

Table 1. The 20 Largest US Metropolitan Areas

Metropolitan Area	Population (millions)	Area (km^2)	Color*
New York–N. New Jersey–Long Island, NY–NJ–CT–PA	20.1	17,534	Black
Los Angeles–Riverside–Orange County, CA	15.8	9505	Black
Chicago–Gary–Kenosha, IL–IN–WI	8.8	8140	Black
Washington–Baltimore, DC–MD–VA–WV	7.3	11,425	Black
San Francisco–Oakland–San Jose, CA	6.8	3785	Dark
Philadelphia–Wilmington–Atlantic City, PA–NJ–DE–MD	6.0	9609	Light
Boston, MA–NH	5.6	13,294	Dark
Detroit–Ann Arbor–Flint, MI	5.5	8363	Light
Dallas–Fort Worth, TX	4.8	5880	Black
Houston–Galveston–Brazoria, TX	4.4	6069	Light
Miami–Fort Lauderdale, FL	3.7	2389	Black
Atlanta, GA	3.7	7955	Light
Seattle–Tacoma–Bremerton, WA	3.4	5352	Dark
Cleveland–Akron, OH	2.9	5771	Light
Minneapolis–St. Paul, MN–WI	2.8	4345	Dark
San Diego, CA	2.8	3175	Light
St. Louis, MO–IL	2.6	4102	Light
Pittsburgh, PA	2.3	6594	Black
Phoenix–Mesa, AZ	2.9	2387	Dark
Tampa–St. Petersburg–Clearwater, FL	2.3	3052	Light

**Color scheme as shown in Figure 3, B–D.*

terms of the competition for resources between cities—that is, individual city footprints versus nonoverlapping footprints. We restricted the extent of our study to the contiguous lower 48 US states and computed EFs simultaneously for the 20 largest US metropolitan areas. We expected that EF size would increase with competition for resources.

Study Area

Greater Phoenix is a rapidly growing urban center located in the southwestern United States and entirely isolated within the Sonoran Desert. The study area, including the 24 municipalities of the Phoenix metropolis, is 2387 km^2 in extent, and supports a population of over 2.9 million inhabitants (US Census Bureau 1998). The surrounding wild lands of the Sonoran Desert are characterized as semi-arid to arid lands with soils of low permeability and moisture. Local rainfall averages less than 200 mm/y, and actual evapotranspiration exceeds 95%. The vast majority of resources—including food, water, fossil fuels, and electricity—must be imported to meet the demands of its growing population.

Phoenix was established in 1867 at the confluence of two large rivers, the Gila and the Salt. In its early years, the city relied exclusively on surface water, but it made increasing use of groundwater as its population grew and agricultural activities expanded. Today, approximately 49% of the water for metropolitan Phoenix is supplied by the Salt River, 27% is pumped from groundwater, and about 24% is imported from the Colorado River (ADWR 1994). Groundwater is being withdrawn at unsustainable rates due to the combined pressures of the city's location in the arid Sonoran Desert and the rapid growth of its population. To meet long-term projections of water demand, the Central Arizona Project (CAP) canal was constructed in 1986 to divert an allocation of water from the middle and upper Colorado River to the Phoenix and Tucson metropolitan areas.

For purposes of interurban comparison, we also obtained 1998 population and area data for the 20 largest cities in the United States (Table 1) (US Census Bureau 1998). Although per capita requirements tend to vary from one area to another, we used the Phoenix per capita requirements for all cities to facilitate comparisons between cities and examine the influence of regional heterogeneity.

Data Description

Precipitation data were obtained from PRISM (Parameter-elevation Regressions on Independent

Slopes Model) and represent the mean annual precipitation for 1961–90 (Daly and others 1994). Actual evapotranspiration data were derived from a global model produced by Ahn and Tateishi (1994). The digital elevation model (DEM) used to delineate the CAP canal watershed in the Colorado River drainage was developed by the United States Geological Survey (USGS) EROS Data Center. The drainage basin was computed using WATERSHED in ArcInfo 8.0.2 (ESRI 2000). The renewable water source was calculated as the difference between spatially explicit maps of precipitation and actual evapotranspiration, and may take the form of surface water runoff or groundwater recharge. Resulting negative values were set to zero. Water consumption was calculated using a 10-year (1985–94) average of the annual per capita usage of total municipal water (335.83 m^3/y) for the Phoenix metropolitan area (ADWR 1994). Because the calculation of renewable water is confounded by its interaction with agriculture, a conversion figure of an additional 2000 m^3/y was included, based on estimates of crop water usage from the United Nations Food and Agriculture Organization (FAO) (Klohn and Appelgren 1997). We assumed that the remediation of urban wastewater (that is, sewage) occurs internally to the city and therefore did not include this factor in our analysis.

A spatial map of food production was generated from a US Department of Agriculture (USDA) database for 1998. This database contains records of both the annual crop area planted and the amount of crops harvested by type for each county in the United States. We extracted the data for the seven dominant agricultural food crops: wheat, corn, barley, rye, soybeans, potatoes, and oats. Because all crop harvests except potatoes were reported in bushels, these values were converted from units of volume to mass using conversions adopted by the Chicago Board of Trade. The mass of harvested crops was converted to kilocalories based on conversion factors used by the United Nations FAO statistics database. Total kilocalories for each county were converted to a sustainable human population size existing on a diet of 2500 kcal per person per day.

In addition to the resources required as inputs into a city, we also examined the appropriation of ecosystem services that absorb urban waste. Carbon export from the city was estimated on a per capita basis using 1996 US rates of 5.61 metric tons of carbon annually (Marland and others 1999). Carbon dioxide is assimilated into terrestrial biomass during primary production. The actual measure of ecosystem carbon assimilation is net ecosystem productivity (NEP), defined as autotrophic photosynthesis minus the total respiration of all organisms in the ecosystem. This is in contrast to the rate at which an ecosystem obtains carbon, net primary production (NPP), defined as autotrophic photosynthesis minus autotrophic respiration. In this analysis, we used 1% of NPP as an estimate of potential carbon assimilation (NEP) rates (Agren and Bosatta 1996). We used a spatially explicit 40-year-mean estimate of NPP generated by the Century model as part of the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) (Schimel and others 1997). Modeled data were used because accurate alternatives do not exist, and modeling is one of the primary methods for extrapolating information between scales. Estimating NPP at the plot scale is difficult, and translating these plot estimates to larger scales is even more so (Scurlock and others 1999). The Century model has been validated repeatedly in a variety of ecosystems where appropriate environmental data exist and thus may provide the best available estimates of NPP.

Spatial data sets were converted to 10×10 km grid cell sizes and projected in Albers conic equal-area using ArcInfo 8.0.2 (ESRI). Data were converted to grids in ASCII format; the EF algorithms were written and compiled using Visual C++ (Microsoft 2000).

METHODS

The EFs for renewable Phoenix water were computed from two points, the Phoenix urban center and the CAP canal portion of the Colorado River watershed. The CAP canal EF uses the connection of the canal with the Colorado River as its starting point; it includes a consideration of the water appropriated from the watershed upstream from this point and takes into account the 209,780 m^3/y lost to evaporation during transport. The existence of the CAP canal system helps to simplify the water analysis for Phoenix in that it is essentially a point source of water for the city; therefore, it is realistic to assume that water is collected from specific areas in a watershed rather than from some diffuse area surrounding the city. The water EF was calculated in two ways—first including and then excluding the agricultural interaction, based on the average production values for the same crops used to compute the agricultural EF. The consumption of water to produce agricultural crops was calculated as an additional EF measure (hereafter, water EF with agricultural interaction).

Using mean values and methodology developed by prior researchers (Wackernagel and Rees 1996),

Table 2. Various Algorithms Used to Calculate Nonspatial and Spatial EFs

Method	Function
Nonspatial (U.S. mean; Phoenix mean)	REQ × POP / RES_{mean}
Minimum Area	REQ × POP / $RES_{spatial}$; Neighbors
Variable Weighted Distance	REQ × POP × DIST / $RES_{spatial}$; Neighbors
Minimum Distance (circle)	REQ × POP × DIST / $RES_{spatial}$

REQ, per capita resource requirement; POP, urban population; RES, ecosystem resource production per unit area; DIST, distance
DIST may be nonlinearly weighted (for example, a polynomial function of distance, based on a road network) to account for transportation costs.
"Neighbors" indicates that the spatial search for the next pixel is dependent on pixel values adjacent to the EF at the current iteration.

we calculated a nonspatial EF for each resource in two iterations—one based on the mean US national yield and the other on the mean Phoenix yield. We also constructed two new algorithms to calculate the EF in a spatially explicit fashion: the minimum-area EF and the minimum-distance EF (Table 2). The minimum-area EF calculates the minimum EF contiguous to a city. With the resources in a raster format, the algorithm begins by first selecting the cell in which the city center is located. In the minimum-area EF, the resource values for a particular ecosystem service of the neighbors of that cell are evaluated, and the neighboring cell with the highest value is added to the EF. The resources contained in the EF are summed, and the cells neighboring the EF are again evaluated. If the EF becomes "stuck" (that is, isolated by another footprint and/or by geographic boundaries such as coastlines or borders), the algorithm "jumps" by searching for and adding the available cell nearest the existing EF. Cells with resource values of zero are added to the EF but are not included in the EF area. The second alternative analysis we conducted, the minimum-distance EF, involved incrementally expanding the EF around the city in a circle while tabulating the resources within the EF. In both cases, the algorithm stops and the EF is calculated when the resources in the EF are sufficient to supply the requirements of the urban area. Additional EFs were computed for the 20 largest US metropolitan areas in rank order of population using the minimum-area (contiguous) algorithm. Finally, to investigate the effects of regional-scale spatial heterogeneity, the minimum-area EF was expanded from Phoenix to the entire land area of the United States.

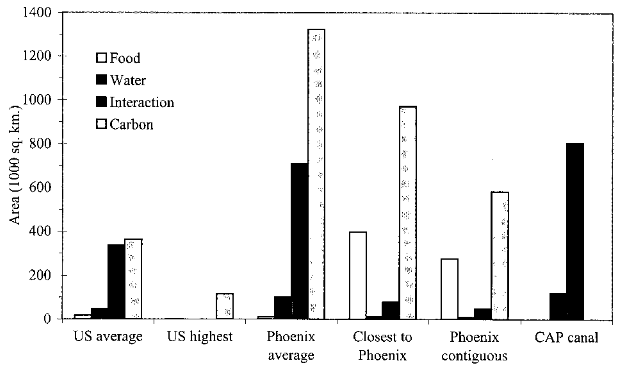

Figure 2. A comparison of EF areas resulting from different methodologies. Some of the values for the US highest EF are too small to be shown on the chart. The importance of spatial heterogeneity is particularly evident in the contrasting patterns of food and water between the Phoenix average EF (nonspatially explicit) and the Phoenix contiguous EF (spatially explicit).

Results

The nonspatial footprint required to generate a sustainable water supply for Phoenix (not including agricultural uses) from local average runoff was 102,000 km^2 (Figure 2). Taking the spatial distribution of resources into consideration, the minimum area contiguous to Phoenix required to meet the city's total water needs was 10,500 km^2, whereas the area required to supply total water consumption using solely CAP canal water was 122,000 km^2 (Figure 3A). Incorporating agricultural usage increased consumption of the renewable water supply almost seven-fold; the nonspatial footprint needed to generate a sustainable water supply that included agricultural interaction was 709,000 km^2. Using the spatial distribution of resources, the minimum area contiguous to Phoenix required to supply the total water consumption including agricultural interaction was 51,000 km^2, or about five times the value for nonagricultural water use. The minimum area to support the city's water needs was 300 km^2 excluding agriculture and 1800 km^2

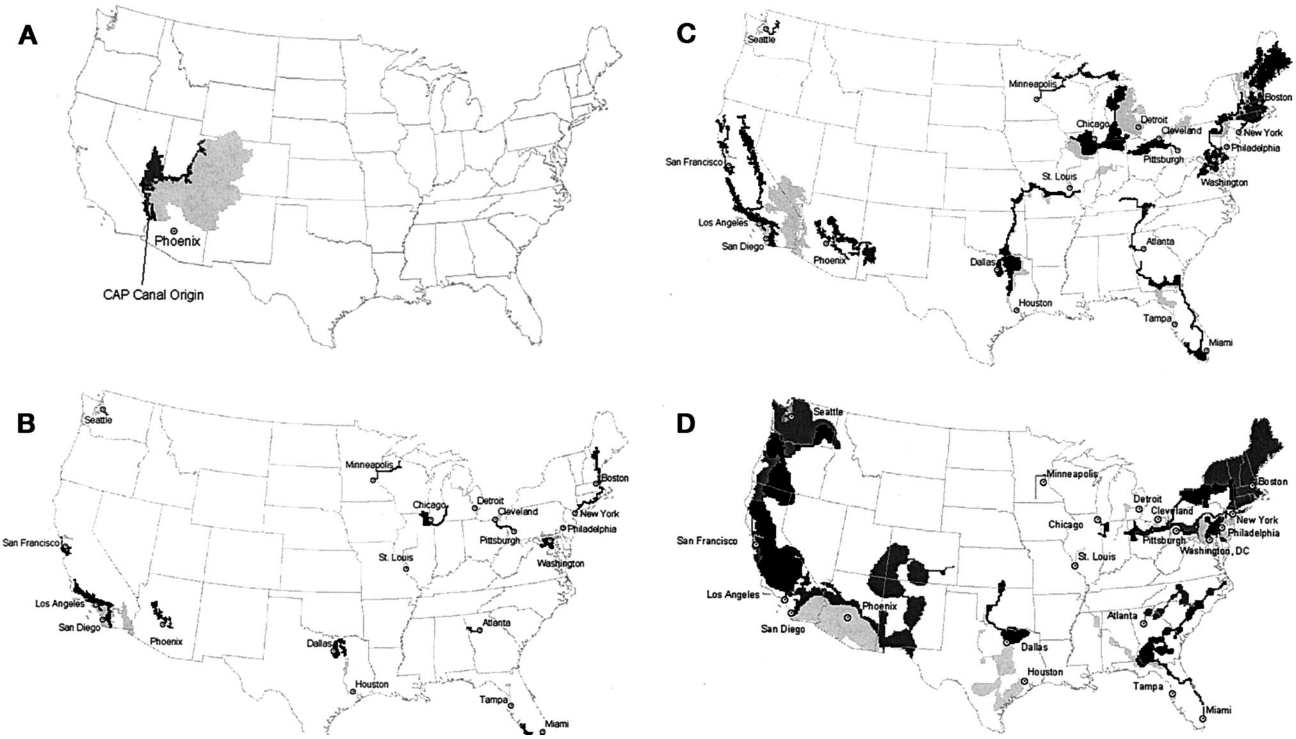

Figure 3. (**A**) Ecological footprints for the Central Arizona Project (CAP) Canal. The minimum-area water-only EF is shown in black, and the EF for water with agricultural interaction is shown in dark gray; the entire CAP watershed includes both of these EFs plus the light gray area. (**B**) EFs for renewable water. (**C**) EFs for water including agricultural interaction. (**D**) EFs for agricultural food production. The EFs for each city are nonoverlapping and are shown in different shades of gray. A breakdown of the color scheme is given in Table 1.

including agricultural usage, as computed using values from the highest-yielding area in the United States.

The spatial footprints needed to supply water to the 20 largest US cities varied in size in correspondence with climatic variations (Figure 3 B, C). Water EFs, both with and without agricultural interaction, often appear to be linear because they follow elevational, latitudinal, and longitudinal gradients in precipitation and evapotranspiration. The maximum population supportable by the total amount of runoff in the contiguous 48 states is 4.69 billion people; however, when water usage for agriculture is taken into account, that figure drops precipitously to 674 million.

The nonspatial EF required to generate a sustainable food supply for Phoenix was 11,000 km^2 (Figure 2). When the spatial distribution of resources is considered, the minimum area contiguous to the city needed for the total food consumption is 278,000 km^2. The maximum population supportable by agricultural production in the contiguous 48 states is 1.26 billion. Food EFs for the 20 largest US cities varied with agricultural production (Figure 3D). The minimum area needed to supply Phoenix with food resources is 850 km^2, as computed from values for the four highest-yielding US counties.

The nonspatial area required to assimilate the carbon emitted from Phoenix is 1,324,000 km^2, but the corresponding figure for the spatially explicit contiguous model is 584,000 km^2 (Figure 2). The footprint for carbon assimilation is by far the largest EF of the three resources evaluated, regardless of method. The minimum area that would be needed to assimilate the carbon emitted from Phoenix is 117,000 km^2. The United States which is able to assimilate carbon for the emissions of 62.9 million people, cannot absorb all of the carbon emitted from the 20 largest US cities and hence is a net exporter of carbon.

Our analysis of the 20 largest US cities showed that location had a striking influence in relation to regional environment (Tables 1 and 3). Only one city (Seattle) had a water EF smaller than the city area after accounting for agricultural interaction, while five cities (Chicago, Cleveland, Detroit, Minneapolis, and St. Louis) had smaller food EFs than their respective city areas. The

Table 3. Minimum-Area (Contiguous) EFs for the 20 largest US Metropolitan Areas

Metropolitan Area	Water EF (km^2)		Water with Agricultural Interaction EF (km^2)		Food Production EF (km^2)		Carbon Assimilation EF (km^2)
	I	C	I	C	I	C	I
New York, NY	11,700	11,700	76,200	76,200	68,400	68,400	1,301,400
Los Angeles, CA	22,800	22,800	69,400	69,400	294,800	294,800	1,540,100
Chicago, IL	10,400	10,400	71,000	71,000	5800	5800	540,600
Washington, DC	6800	6800	42,500	42,500	20,100	20,100	477,100
San Francisco, CA	5200	5200	17,500	17,500	242,600	80,200	402,000
Philadelphia, PA	5700	5900	37,300	29,300	18,900	29,200	347,500
Boston, MA	3400	3400	20,500	29,500	24,300	80,500	368,400
Detroit, MI	7200	7200	43,500	54,500	7900	7900	351,800
Dallas, TX	10,400	10,400	54,400	54,400	37,400	37,400	303,300
Houston, TX	8100	8200	48,500	44,400	117,800	106,700	247,900
Miami, FL	5900	5900	33,300	33,300	67,200	67,200	226,100
Atlanta, GA	2700	2700	16,400	16,400	48,300	37,600	232,200
Seattle, WA	800	800	3400	3400	21,000	61,700	224,300
Cleveland, OH	2900	2900	17,300	17,300	5400	5900	193,000
Minneapolis, MN	4400	4400	22,700	22,700	3700	3700	180,900
San Diego, CA	4100	19,800	26,700	125,300	169,300	169,800	182,300
St. Louis, MO	4200	4200	21,200	24,700	2400	2400	144,300
Pittsburgh, PA	3100	3100	14,700	20,700	10,900	8900	157,800
Phoenix, AZ	10,300	10,300	50,900	50,900	277,100	313,800	583,800
Tampa, FL	3000	3000	17,500	18,200	49,600	38,600	121,200

I, independent; C, resource competition (nonoverlapping)
Note that the EF area for carbon assimilation under competition is greater than the available area (contiguous US).

water EFs (including agricultural interaction) for the 20 largest US metropolitan areas are on average two times larger than their food EFs. City population size is more highly correlated to EF areas than is city area, and water EFs are more strongly correlated to city population and city area than are food EFs (Table 4). There was a trend for EF size to be related to city population and city area; this relationship was strongest for carbon assimilation. The most striking examples of competition for resources were found for water EFs with agricultural interaction (with the strongest competition between San Diego and Los Angeles) and agriculture EFs in the Northeast and on the West Coast of the United States (Figure 3 C, D).

If we expand the EF for Phoenix to the whole of the lower 48 states, the influence of regional heterogeneity on different ecosystem services becomes evident (Figure 4). The curves are steeper for areas that generate more ecosystem services and where the highest proportion of resources are appropriated first, then they level off as less productive areas with lower population densities are incorporated.

Table 4. Relationship between EFs for Ecosystem Services and City Population and City Area for the 20 Largest US Metropolitan Areas

Ecosystem Service	City Population	City Area
Water	0.5247	0.0938
Water with Agricultural Interaction	0.5417	0.2077
Food	0.0747	0.0460
Carbon Assimilation	0.8625	0.3485

Values are linear regression r^2.

The interesting pattern that emerges from this consideration of regional heterogeneity reflects regional differences—for instance, between the arid west and the mesic east regions. These differences are especially striking for carbon and water. As predicted, the response is nonlinear and shows the influence of spatial heterogeneity and the effects

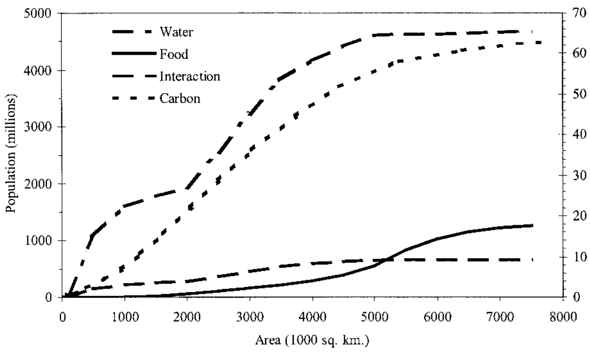

Figure 4. Differences between ecosystem services and the influence of spatial heterogeneity are evident in the nonlinear EF area versus supportable population as the EF is expanded from Phoenix to include the entire lower 48 US states. The area required for the assimilation of carbon emissions is shown on the right y-axis.

that arise when different ecosystem services are evaluated.

Discussion

The urban funnel model of human–ecological interactions reveals the disparity in terms of scale and location between the appropriated ecosystems and the urban ecosystem itself. Although the model can be used to study the ways in which wild or rural ecosystems change in response to urbanization, it also suggests how approaches that incorporate some aspects of human socioeconomic systems can help us to understand the impact of human practices on ecological systems. Socioeconomic institutions can act to buffer the effect of small-scale environmental heterogeneities by implementing technological solutions (such as efficient machinery) and creating transport networks that effectively remove local ecological constraints. However, we cannot expect attempts to integrate human systems and ecosystem processes to be productive if the scales of interaction are not identified correctly. Much of the historical confusion and frustration that has arisen when such attempts were tried at the scale of the city may well be the result of trying to integrate two systems that operate at different scales. The urban funnel model is one approach that can be applied to resolve these disparatities of scale, using EF analysis to estimate the constraining scale.

Our modification of the EF calculation improves on the traditional method by taking a spatially explicit approach. It allowed us to make a quantitative determination of the appropriate scale of human–ecosystem interaction by using several spatially explicit algorithms for three distinct ecological resources. In addition, our method incorporates a distance-weighted distribution of these resources, arrived at by dividing the resources by distance from the city; thus we can identify an entire spectrum of contiguous footprints that show how resource return decreases as distance from the city increases. Using this methodology, the effect of distance, and therefore transportation costs, could be controlled by multiplying distance by a constant. We believe that this is a good start toward the development of EFs that realistically incorporate transportation.

In an attempt to improve on the accuracy of EF estimation, we modeled the interaction that exists between water and food because modern agricultural production is highly dependent on the water supplied via irrigation. In fact, actual water consumption for crops is probably intermediate between the two EF values. There is some double-counting involved in our estimates of crop water usage, because at least part of that amount is also accounted for in the subtraction of actual evapotranspiration. However, even though our inclusion of the interaction term creates EF values that are larger than actual water consumption, our figure probably still represents a conservative estimate because our calculations did not include the high demands for water to produce livestock, an essential element of the typical nonvegetarian diet (Klohn and Appelgren 1997). Wackernagel and Silverstein (2000) suggest that a conservative estimate of indicators be used to quantify sustainability, and our calculation of a minimum EF is in agreement with their recommendation. However, perhaps the most important result of our calculation is the finding that the capacities of terrestrial ecosystems to assimilate gaseous waste may be more limiting to humans than any constraint on their resource production.

A comparison of the water and food footprints reveals that there are distinctions between the size of the areas needed to supply individual resources. In both cases, the mean values of the nonspatial EFs for the US and Phoenix differed by up to two orders of magnitude (Figure 1). Similarly, a comparison of nonspatial and spatially explicit EFs shows the important influence of the heterogeneity of resources. For example, if we examine the nonspatial average for Phoenix, we see that water is the limiting resource: 11,000 km^2 is needed to supply food, 102,000 km^2 for water, and 709,000 km^2 for water with agricultural interaction. However, spatially explicit methods show just the reverse, with food requiring approximately 30 times as much land area as water and five times as much area as water when agricultural interaction is included.

Further modifications to our model could generate an even more realistic estimate of the area required to meet the demands of resource consumption and waste assimilation. For example, this analysis might be improved by the incorporation of temporal heterogeneity. Renewable water resources may be spatially or temporally inaccessible as a result of physical constraints or the inability to collect all surface runoff (for example, due to water retention in dams and reservoirs) (Postel and others 1996). Desert soils such as those associated with Phoenix, are highly impermeable, and runoff in the Sonoran Desert occurs most commonly in the form of infrequent but intense events, often as flooding. This may lead to a greater instantaneous actual runoff than would be expected from an annual average, since the effects of evapotranspiration are reduced. Also, the potential discount or augmenting effect inherent to living in a city can alter the per capita use of resources. An analytical approach to these issues would make the estimates more accurate, but it would also decrease the useful simplicity inherent in the EF.

It is important to consider that remote, external ecosystems within the EF are not immune to the effects of the human appropriation of ecosystem services. Even though our calculation of the renewable water supply incorporates transpiration by vegetation, the complete removal of the remaining water would have severe ecological effects. For example, fishes, riparian trees and birds, insects, and other fauna are also dependent on the ecosystem services supplied by intact aquatic ecosystems with a minimum instream flow. Human appropriation of that flow could impair the functioning of entire ecosystems (Holling 1986). The realistic consequences of the human appropriation, through direct and indirect feedback mechanisms, include alterations to the ecosystem structure, function, and dynamics of these systems, resulting in decreased productivity and lowered resilience (Peterson and others 1998; Rockström and others 1999).

As a solution to this dilemma, instead of appropriating all of the available resources in the EF for human use, we propose that some minimum level of ecosystem resources be reserved for ecosystem functioning in the interests of maintaining biodiversity and ecosystem integrity. We can easily modify our analysis to make a proportion of resources unavailable for human appropriation so that it remains in the ecosystem. This modification offers a means of controlling for the tradeoff between human appropriation and ecosystem requirements. If we could identify the relevant parameters by analyzing the ecosystems within the EF and modeling their resilience or sustainability, we might be able to apply the EF concept to ecosystem management.

Currently, there is no EF analysis designed to model the changes in ecosystem dynamics that result from human appropriation, but we have begun to identify some methods that could be used to determine the requirements essential for the maintainence of ecosystem structure. For example, we used a conservative value for NEP/NPP of 0.01 (Agren and Bosatta 1996). However, other investigators have used NEP/NPP values ranging from 0.15 (Kolchugina and Vinson 1993) to 0.24 (Turner and others 1995), and young forests that are actively sequestering carbon may temporarily have even higher rates. The incorporation of temporality as a factor in ecosystem parameters could help to reconcile EF analysis with ecosystem dynamics.

EF analysis is a potentially useful heuristic device to portray the sustainability of human systems in relation to the production of ecosystem services (Wackernagel 1999; Deutsch and others 2000). Our own work is in line with the intentions of Deutsch and others (2000), who use the EF to examine the interaction of humans and nature. As Wackernagel (1999) states, "[The EF] is one of the few ecological measures that compares human demand to ecological supply." Our analysis does not include any policy recommendations for sustainable management. Instead, our investigation focuses on coarse-scale human–ecological dynamics that may help us to understand the human socioecological system and its interaction with other ecosystems. As the computer revolution continues to transform human institutions, the evaluation of EFs in alternative currencies (such as information or technology) can be expected to provide further insight into the dynamics of human–environment interactions. The power of the EF lies in its ability to convey an easily understood message about the interaction between an urban system and its environment, and our modification of traditional EF analysis improves on the method by allowing more accurate estimates of the scales of that interaction.

An integration of human and nonhuman ecological processes should incorporate multiple scales. Because there are scale-related differences between the urban and regional landscapes, we need to define and understand the urban ecosystem in terms of interactions among separate natural and human ecosystems. Ecologists can answer questions about the effect of human practices on native ecological processes. Social scientists can predict how humans will invade the landscape. But even if our environmental policy is directed toward some goal of sustaining native processes, this policy will ultimately be enacted through a concatenation of economic, institutional, and political forces. Our conceptual model provides the framework needed to relate the social dynamics localized within a city to broader, regional ecological processes.

Despite its evident advantages, EF analysis has also been subjected to strong criticism. For example, van den Bergh and Verbruggen (1999) cited several problems with the traditional EF concept and questioned both its heuristic utility and its applicability to planning. Among the major criticisms are its inherent assumptions that land has one exclusive use, resources are distributed homogeneously, and transportation networks should be used to redistribute appropriated resources. More recently, a the journal *Ecological Economics* (2000; 32:341–394) presented a forum debating the pros and cons of the EF. Problems related to trade, social and ecological dynamics, and spatial scale have all been obstacles to its full acceptance. One of the main bones of contention concerns the interpretation of the EF in science versus policy. Thus far, practitioners of the basic and applied—or alternatively, biological and social—sciences have been unable to come to an agreement about the details and purposes of the EF.

Although these concerns are valid, we believe that several of these divisive issues can be resolved. In particular, the importance of spatial location and the heterogeneous distribution of resources, has generally been overlooked, but these factors could be useful in reconciling some of the arguments. For example, rather than viewing trade as a pitfall of the EF, we think that a regional, spatially explicit EF would allow the necessity for trade to be factored into the analysis. Spatial heterogeneity in the distribution of resources has further implications for the results of EF analyses. By computing individual, spatially explicit EFs simultaneously for various resources based on where the resources actually occur, we can avoid the assumption that land has only one use. When EFs are calculated for multiple ecosystem services, the EFs for a particular resource may overlap different resources and need not correspond to, or even occur at the same magnitude as the EFs for other resources. Our results show how the spatial competition for resources generally increases EF size, but they also indicate, perhaps surprisingly, that competition can decrease the EF in certain situations.

Although our EF is computed in a spatially explicit manner, it is incorrect to assume that it represents the area from which the ecosystem services are actually acquired. For example, trade and transportation redistribute resources drawn from distant hinterlands. In addition, transportation introduces costs (losses due to inefficiencies) that are not incorporated in our analysis, except for those accounted for by water evaporation during transport along the CAP canal to Phoenix. Redundancy also exists with ecosystem services; no single location is critical for the supply of any single resource. This redundancy both increases the stability of resource importation at large scales and reduces the perceived feedback from ecosystem services at local scales.

By factoring transportation into our analysis of multiple cities, we indirectly consider the effect of regional heterogeneity, thereby incorporating ecosystem dynamics. This aspect of our analysis raises the question of whether it is more ecologically sustainable for a city to exist in an area of higher or lower potential for resource production—that is, allowing for differing levels of ecosystem resilience to disturbances caused by the human appropriation of ecosystem services. By analogy to the Leibig-Sprengel Law of the Minimum, determining the size of the area required to supply the individual resources needed to support urban growth can help to identify the environmental factors that have the greatest impact on that growth; however, analysis is complicated by the use of imported and nonrenewable resources.

The spatially heterogeneous EF is consistent with other concepts in biology. Some social organisms, such as ants and bees, utilize ecosystem services derived from the environment beyond the colony's primary residence. Similarly, the home ranges and migrations of animals are dependent on the availability of environmental resources. Limitations to their local availability affect and may ultimately constrain the growth of the organism. In like fashion, if the internal resources of a city are not enough to support its needs, resources produced elsewhere need to be obtained. However, since the EFs of two cities cannot overlap, competition forces the city to either import resources from distant areas or expand its EF into less productive areas.

The conceptual basis of this analysis can be linked to the related multidisciplinary ideas of ecological neighborhoods, ecological field theory, and meteorologically defined footprints. Addicott and others (1987) defined the three properties of the ecological neighborhood as "an ecological process, a time scale appropriate to that process, and an organism's activity or influence during that time period" and hypothesized that they are responsible for the spatial and temporal patterning of environments. Studies taking this approach commonly focused on density-dependent competitive processes; for example, the concept of the ecological neighborhood has been applied and tested empirically with plants, where neighborhood interactions ranged from absent to important in influencing the growth of plants under competition (Silander and Pacala 1985; Pacala and Silander 1990). Similarly, ecological field theory quantifies plant spatial influences as variable regions around individual plants (Wu and others 1985; Walker and others 1989). Another form of footprint analysis has been used in meteorology (Wilson and Swaters 1991); in this type of analysis, an estimate is made of the upwind source area that influences measurements at a downwind sampling point. This is the area where the diffusion of airborne particles occurs; the footprint is dependent on the particle properties and wind patterns. As is also seen with the spatially explicit EF, the spatial distribution of factors external to the local scale is important, in ecological neighborhoods and meteorological footprints.

In general, the competition for resources increases the EF; however, EFs can also shrink due to interurban competition because a competing city's EF may force the focal EF out of a high-production, but isolated, region, into an area where there is higher production of ecosystem services (Table 3). This phenomenon did not occur in the water-only EF, but it appeared twice in the water EF with agricultural interaction due to the increased competition for resources. It occurred five times in the food EFs for the 20 largest US cities, and the total EF area of all 20 cities was smaller under the competition condition than independently. Because the algorithm computed EFs for cities in order of population, the largest cities were less affected by spatial competition for resources than the smaller ones. Competition among the 20 cities increased the water footprints by 10%–20%; San Diego had the largest increase in the EFs for all resources due to the influence of competition. Incorporating additional cities within the same region increases the degree of competition and consequently the size of the EF.

Our results highlight several characteristics of human–ecosystem interaction that were captured by the urban funnel model, with its emphasis on the disparity of scales between cities and external ecosystems. First, the incorporation of the spatial heterogeneity of resources had a profound effect on the EF analysis when compared to nonspatial EFs. The EFs resulting from the various methods show dramatic contrasts that reflect the local biogeophysical environment. Second, the algorithms we used for our analysis of a spatially heterogeneous EF suggested some improved methods of EF analysis, that may help to address some of the issues raised by its critics. Third, we found that the specific resource used in the calculation can have a large effect on the EF analysis; this finding underscores the important influence of city location on the interaction with local ecosystem services. Fourth, the model allowed us to address the interactions between ecosystem services; these interactions play an important role in socio ecological dynamics, but they have often been overlooked.

We humans are unique in our capacity to directly affect an extremely wide range of scales, yet it is primarily at the larger scales that we are ecologically constrained. For the modern city, which can derive all of the requirements needed to sustain human habitation from external, sources, there may be no strong or constraining feedback that operates at an internal or local ecological level. The urban funnel model is a promising first step toward the design of conceptual and analytical models that incorporate the appropriation of external resources. Finally, we believe that the inclusion of spatial information in models of complex dynamic process can enhances our understanding of the interactions between humans and the ecosystems upon which they depend.

ACKNOWLEDGMENTS

We appreciate the constructive comments of John Briggs, Diane Hope, Amy Nelson, Weixing Zhu, the Arizone State University (ASU) Landscape Ecology and Modeling laboratory, the ASU Ecosystems/Desert Stream laboratory, and the ASU Geographic Information Systems laboratory. Carl Folke and two anonymous reviewers provided useful and critical suggestions. This work was supported by the National Science Foundation, grant number DEB-97-14833, in support of the Central Arizona–Phoenix Long-Term Ecological Research (CAP LTER) project.

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