Myrna H. P. Hall
Stephen B. Balogh
Editors

Understanding Urban Ecology

An Interdisciplinary Systems Approach

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This book is dedicated to H. T. Odum, whose inspiration led to the development of ecological engineering, biophysical economics, ecological economics, ecological modeling, and emergy analysis, all of which apply ecology to understanding and solving environmental problems in human-dominated ecosystems. At least eight of the authors of this book are academic "children" or "grandchildren" of Dr. Odum.

We also owe a debt of gratitude to the small but highly influential band of the State University of New York College of Environmental Science and Forestry (SUNY-ESF) professors who, in the 1970s, laid the groundwork establishing the academic disciplines of urban forestry, urban meteorology, and urban soil science. They include Dr. Norman Richards, Dr. Rowan Rowntree, Dr. Lee Herrington, and Dr. Phillip Craul.

Preface

This textbook grew out of The Urban Initiative at SUNY College of Environmental Science and Forestry (SUNY-ESF), just as the new millennium was dawning (year 2000), which addressed the challenge of promoting environmental literacy in an ever-more urban world. Then President of ESF, Dr. Neil Murphy, stated:

> While many people associate the environment with wild lands and linked rural areas, the most important environmental and quality-of-life issues of the coming decades will be related to the urban environment.

A program in urban environmental science was intended to appeal to:

> All students, but perhaps especially those with an intimate knowledge of the challenges facing city inhabitants …. who can make professional contributions on issues ranging from urban forestry and urban wildlife to urban air and water quality, waste disposal, population growth and urban sprawl, sustainability assessment, and environmental justice and equity.

Faculty members felt that a course in Urban Ecology would provide students with the basic knowledge they would need to approach these issues from a systems perspective. The course was designed by an interdisciplinary team of natural and social scientists and faculty members from the Departments of Environmental *Chemistry*, Environmental and Forest *Biology*, *Forest* and *Natural Resource Management*, *Environmental Studies*, Environmental *Engineering*, and *Landscape Architecture*. The result is a field-based course that explores the metabolism of the city. Many of the authors of this book contribute lectures and field exercises to this course.

Understanding Urban Ecology: An Interdisciplinary Systems Approach originated from that effort and that course. The book and accompanying field labs are designed to help students at the college undergraduate level, or those in advanced-standing college-credit high school courses, understand urban environments as ecosystems. It also provides an overview for graduate students and a rich literature base on the topic. The ecosystem perspective, emphasized throughout, includes quantifying the flows of energy, nutrients, and materials required to make cities function, the controls on those flows imposed by nature and human decision-making, and the consequences to both biological and social quality of life that come from altering "natural" flows. Students are led to trace the flow and transformation of energy and materials in, out, and within the urban ecosystem; the biophysical, social, and cultural factors that influence those flows; the resulting structure of the urban environment; and the environmental, economic, and social consequences of the structural and functional transformations that occur. Feedbacks, particularly those growing out of people's perceptions that influence decision-making by individuals, businesses, and government, are emphasized. Unlike most approaches to urban studies, the systems approach put forth in this book will give students not only a basic understanding of the fundamental importance of natural resources to the continued operation of cities and the effects of urbanization on hydrology, climate, air quality, etc. but also the tools to quantify and analyze the connections between the environmental and the socioeconomic subsystems of a city with the ultimate goal of assessing and generating sustainable urban systems.

The major organizing concept of this book is social-ecological metabolism, that is, the flows of biotic and industrial energy in the city and its surroundings. System "health" and "sustainability" are evaluated in terms of both social (S) and ecological (E) metabolism. The concept of metabolism and its associated properties allows evaluation of the many factors that contribute to an organism's or an ecosystem's biological health and can be used as a metaphor for society as a whole. The ecological analyses outlined in this book focus on the biophysical realm primarily in the form of energy, material, and nutrient inputs and outputs, derived "power" or "empowerment," and system waste. The social science perspective encompasses studies of both the cultural and economic components that comprise the human dimension of ecosystem processes and include primarily human perception and behavior, institutional behavior, societal cultural norms and preferences, and demographic and monetary flows. The S-component, like the E, is both a driving agent of urban ecosystem structure and function and receiver of impacts due to alteration of structure and function away from what we deem "natural" ecosystem processes. Because we take the view that humans are part of nature, we use "natural" to distinguish the qualities of ecosystem components like clean air and clean water, or ecosystem functions like the soil's ability to filter water, as they existed prior to human management and control. The demand by humans for an ever-more comfortable lifestyle, especially after the introduction of fossil fuels, has enormously accelerated the flow of nutrients and materials through the urban ecosystem, usually leading to stressed biological environments and the ecological conditions on which all species rely. The case is made that studying how nature works both with and without human intervention is vital to avoiding urban collapse and designing a sustainable future.

The chapters describe one by one the different subsystems of the urban environment, their individual components and functions, and the interactions among them that create the social-ecological environments in which we live. Purchase of the book will provide access to twelve detailed field exercises to promote hands-on experience, observation, and quantification of urban ecosystem structure and function so that students will be able to evaluate proposed policies for urban sustainability in terms of ecosystem capacity, potential positive and negative feedbacks, the laws of thermodynamics, and sociocultural perception and adaptability. The intent is to promote eco-consciousness based on natural science and empiricism rather than intuition and sentiment, the latter of which often lead to counterproductive solutions to urban problems.

The book is structured as follows:

Part I of the book provides definitions of terms, the current global demographics with respect to urban growth, and the pressing issues faced by cities today. It builds the case for why urban ecology is increasingly important as a field of study. The authors present evidence to support our view that the urgent environmental and social issues of the future must be evaluated from an interdisciplinary systems approach if proposed solutions are to be sustainable and not cause nor contribute to counterintuitive effects in some other part of the system, now or in the future. The argument for viewing the city as an ecosystem, generally accepted among urban ecologists, with an emphasis on the social-ecological metabolism approach is presented because we believe it provides students the required base to understand how urban structure and function contribute to or detract from quality of life for both people and other urban dwellers.

Part II looks at the city in history from ancient times to the present. The authors describe the importance of geography, resources, and human decision-making to the metabolism of these cities, i.e., the growth and decline of urban economies. Both papers focus upon the role that energy plays in the development of complex social institutions and upon how a city was limited by the energy available to it. A fundamental transformation occurred in the eighteenth century when the access to fossil energy allowed the development of far greater degrees of complexity, greater specialization and the division of labor, and an expansion of debt to drive economic growth.

Part III chapters are intended to develop students' understanding of eight major social-ecological systems, their structure and function, how they control or are controlled by urbanization, and how they affect social-ecological metabolism *in* urban areas (microscale) and *beyond* (macroscale).

Part IV introduces concepts from land planning, landscape architecture, food studies, and ecological engineering that can help maintain ecosystem functions in the urban environment.

It is our hope that those who read this book will close the last page with a greater appreciation of the amazing complexity of the urban ecosystem, with a better understanding of how the biotic and abiotic components of the urban ecosystem interact and adapt (or fail to adapt) to changing conditions over time, and will be inspired to go out into the world and create novel solutions that will help make the cities of the future resilient to the environmental changes they are currently undergoing and will continue to encounter.

Electronic Supplementary Material

There are 12 labs or field exercises that accompany this text. All have been tested over the years in the Urban Ecology course taught at the State University of New York College of Environmental Science and Forestry. These exercises bring students into direct contact with the structure and function of the urban ecosystem and provide them with hands-on experience. All but two are conducted in the field, and most can be conducted over a typical 3-hour college lab period, two consecutive lab periods, or over a full day's excursion on the weekend. Not all chapters have an associated field exercise, but all chapters should be covered over the course to give students the fullest understanding of urban ecology. The exercises will need to be revised to the particular circumstances of the location where the course is taught. Although developed in a Northeastern US city, the activities can be adapted to any urban conditions and configurations. In some instances, equipment is recommended that may not be available. A clever instructor can devise an alternative means of gathering similar data or choose to leave out an element of the exercise. We hope you enjoy these excursions and the critical thinking required as much as our students have over the years.

Examples of the exercises and the chapter(s) they are best coordinated with are:

Field exercise	Field exercise description	Relevant chapters	Recommended site(s) to visit
1	Analysis of stream water quality along a rural to urban gradient using macroinvertebrates, chemical and physical analysis	1, 6	A stream or creek that flows from the rural environment to the city
2	Analysis of the metabolism of an urban block (Field Ex. 6 may precede)	2, 8	One city block, preferably mixed residential (single-family and apartment homes) and commercial establishments
3	Assessing community risk perception, beliefs, and attitudes	3, 13	Site to be determined based on issue and Institutional Review Board (IRB) permission
4	Urban hydrology and green infrastructure	6	Elements of the urban hydrological system, high points to low points, i.e., contributing zones, flooding zones; green infrastructure installations
5	Urban heat island assessment	7	Various urban sites with different quantities of built versus vegetated land cover
6	Measurement of urban trees to calculate air pollution removal capacity	8	Trees on an urban block or within a remnant urban forest (can be used as input to Field Ex. 2)

Field exercise	Field exercise description	Relevant chapters	Recommended site(s) to visit
7	Analysis of the urban nitrogen flux from the food table to the wastewater treatment plant to local receiving waterbodies	9, 14	Wastewater treatment plant; time permitting—a grocery distribution warehouse; the water body where the sewage effluent is dumped
8	Systems diagramming of the solid waste stream	10	A local waste to energy plant, or other solid waste disposal facility
9	Evaluation of the urban plant community across different biotopes	11	A lawn, wasteland, pavement cracks and walls, and/or park or residential garden, cemetery, downtown industrial landscape installation
10	Urban wildlife adaptation and evolution using *SquirrelMapper*	12	Computer lab
11	Assessment of an environmental justice claim using geographic information systems analysis	13	Computer lab
12	Lead levels in urban soils	13	Field and chemistry lab

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About the Authors

Stephen B. Balogh earned his doctorate from SUNY College of Environmental Science and Forestry (ESF). He currently works as a postdoctoral researcher at the US EPA Office of Research and Development in the Atlantic Ecology Division. He is an environmental scientist who studies communities and their connections to the environment across global, regional, and local scales—including nutrient issues, ecosystem services, energy and material flows, and restoration. He has collaborated with other scientists, academics, and stakeholders on a broad range of interdisciplinary research. These projects range in scale from regional optimization of nitrogen removal interventions in Cape Cod to neighborhood-scale analyses of ecosystem services and material and energy flows resulting from restoration efforts and population dynamics in San Juan, Puerto Rico. Prior to his current position, he worked as a visiting assistant professor at SUNY-ESF and adjunct professor at the Whitman School of Management at Syracuse University, where he taught courses about urban ecology, renewable energy, and sustainable business strategies. His PhD dissertation is entitled "Feeding and Fueling the Cities of the 21st Century." He has published 11 papers and several book chapters on the nexus of the environment, energy, and economy.

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Patrick Kangas is a systems ecologist with interests in ecological engineering, tropical sustainable development, and general ecology. He received his BS degree in Biology from Kent State University, MS in Botany and Ecology from the University of Oklahoma, and PhD degree in Environmental Engineering Sciences from the University of Florida. After graduating from Florida, Dr. Kangas took a position in the Biology Department of Eastern Michigan University and taught there for 11 years. In 1990, he moved to the University of Maryland, where he is an associate professor in the Environmental Science and Technology Department. He has published more than 50 papers, book chapters, and contract reports on a variety of environmental subjects, including the textbook *Ecological Engineering: Principles and Practices*.

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Brandon K. Winfrey studied Environmental Engineering (BS, University of Oklahoma, 2006; MS, Stanford University, 2007) and Environmental Science and Technology (PhD, University of Maryland, 2012). His dissertation focused on developing dynamic emergy accounting models that appropriately allocated emergy in ecosystems and general systems that recycled material. Following this, he shifted his research focus to study ecological aspects of stormwater management by undertaking a postdoctoral scholar position at the University of California, Los Angeles, where he examined plant functional ecology in rain gardens. He currently researches ecological engineering in stormwater management and teaches water engineering as a lecturer in the Department of Civil Engineering at Monash University in Australia.

Part I
Systems Approaches to Understanding How Our Cities Work

Chapter 1
What Is Urban Ecology and Why Should We Study It?

Myrna H. P. Hall

Abstract This chapter introduces urban ecology as an analytical approach to understand how our cities work as ecosystems and to assess trade-offs associated with proposals intended to make our cities more sustainable. We present the concept of social-ecological metabolism and review the fundamentals of systems ecology that we can employ to quantify flows of materials, nutrients, and energy upon which our cities, and thus the majority of the world's population, depend. We make the case that predicted population growth, climate uncertainties, and natural resource declines will present difficult challenges to urban citizens and their leaders, making the study of urban ecology very important to securing more resilient cities in the years to come.

Keywords Urban ecology · Social-ecological metabolism · Ecosystem structure and function · A systems approach

1.1 What Is Urban Ecology?

Urban ecology is the study of the structure and function of man-made environments, how the living and nonliving parts of those environments relate to each other, and the quantification of the flows of energy, materials and nutrients, etc. required to sustain urban systems. Urban ecological studies can be conducted in many ways and at multiple scales. Perhaps most basically there is generally a distinction made between the ecology *of* cities and ecology *in* cities [1]. Studies of the first type are interested in the metabolism of an entire city as an ecosystem with its multiple subsystems that are interrelated. We would categorize this as a systems ecology

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approach to understanding urban metabolism, and it is this perspective that we emphasize in this book. Ecological studies of the second "in city" type are more focused on habitats within the city and how the conditions at those locations alter or drive the structure and function of ecological systems at that level. An example of the former might be the attempt to understand how much area outside the city must be exploited to feed the city's population (see Chap. 14), or to provide unfiltered drinking water, whereas the latter might look at what explains the high number of squirrels frequenting a city park (see Chap. 12) or citizens' attitudes across neighborhoods vis-a-vis different types of green infrastructure proposals that will reduce stormwater runoff (see Chap. 3) and downstream pollution (see Chap. 6). These terms—ecology, structure, function, metabolism, and systems thinking—may be new to you, so let's begin with some definitions.

1.1.1 Urban

The first city-states arose in what is called the Fertile Crescent (Fig. 1.1). The urban development within this region, also known as the birthplace of civilization, is generally associated with the rise of agriculture, religion, writing, history, science, and

Fig. 1.1 The Fertile Crescent, home to the first cities such as Ur and Uruk, from whence the word urban derives. Note that Ur was situated on the Persian Gulf at that time and Uruk on the Euphrates River. Cities were established later in the Nile Valley to the west. Image Source: Sayre [2], p15 with permission of Pearson USA

trade. This is not surprising as the change from hunter-gatherer livelihoods to relatively productive agriculture allowed people to settle in one place and engage in other pursuits besides getting food. The area of warm climate and rich soils, particularly between the Tigris and Euphrates rivers, a region known as Mesopotamia in Greek, Al Jazirah in Arabic, and Iraq today, was probably first settled around 10,000 B.C.E. (before current era). The first city-state, Eridu, dates to about 5400 B.C.E. and was soon followed by *Ur* and *Uruk*, from which the word urban is derived. *Urban* can be defined both quantitatively and qualitatively. Quantitatively, population size or density has been the metric used to define what is a city. The largest city in 3100 B.C.E. was Memphis, Egypt, with over 30,000 people (Table 1.1). Today the US Census Bureau defines *urban* quantitatively as census tracts of >3 mile^2 that have a population *density* of at least 1000 people per square mile and contiguous areas or mixed use (residential/industrial) that have a population density of at least 500 people per square mile [4]. However, an individual person's view of what's *urban* versus *rural* is probably based less on population size or density and more on a qualitative impression that conjures up dazzling city night lights (Fig. 1.2), a jazz festival in the park, the rush and crush of jubilant fans pouring out of a stadium, or perhaps less positive impressions related to the cacophony of a downtown traffic, sewer odors, or homeless people sleeping in the street. Over the centuries people have been drawn to cities as centers of civilization including governing, trade, culture, learning, and entertainment. The hustle and bustle of commerce, employment opportunities, and the arts and cultural events are what attract people to cities and what make cities unique from other habitats. Douglas contrasts *civitas* (the city), origin of the word civilization, the cultural, political functioning of the city from *The Urbs* or the physical form or structure [5]. From an ecological perspective, this

Table 1.1 Year that ancient cities became largest in the world

City	Year	Population
Memphis, Egypt	3100 B.C.E.	>30,000
Akkad, Babylonia (Iraq)	2240 B.C.E.	
Lagaš, Babylonia (Iraq)	2075 B.C.E.	
Ur, Babylonia (Iraq)	2030 B.C.E.	65,000
Thebes, Egypt	1980 B.C.E.	
Babylon, Babylonia (Iraq)	1770 B.C.E.	
Avaris, Egypt	1670 B.C.E.	
Memphis, Egypt	1557 B.C.E.	
Thebes, Egypt	1400 B.C.E.	
Nineveh, Assyria	668 B.C.E.	
Babylon, Babylonia (Iraq)	612 B.C.E.	First above 200,000
Alexandria, Egypt	320 B.C.E.	
Pataliputra (Patna), India	300 B.C.E.	
Changan (Xi'an), China	195 B.C.E.	400,000
Rome, Italy	25 B.C.E.	

Source: Chandler [3]

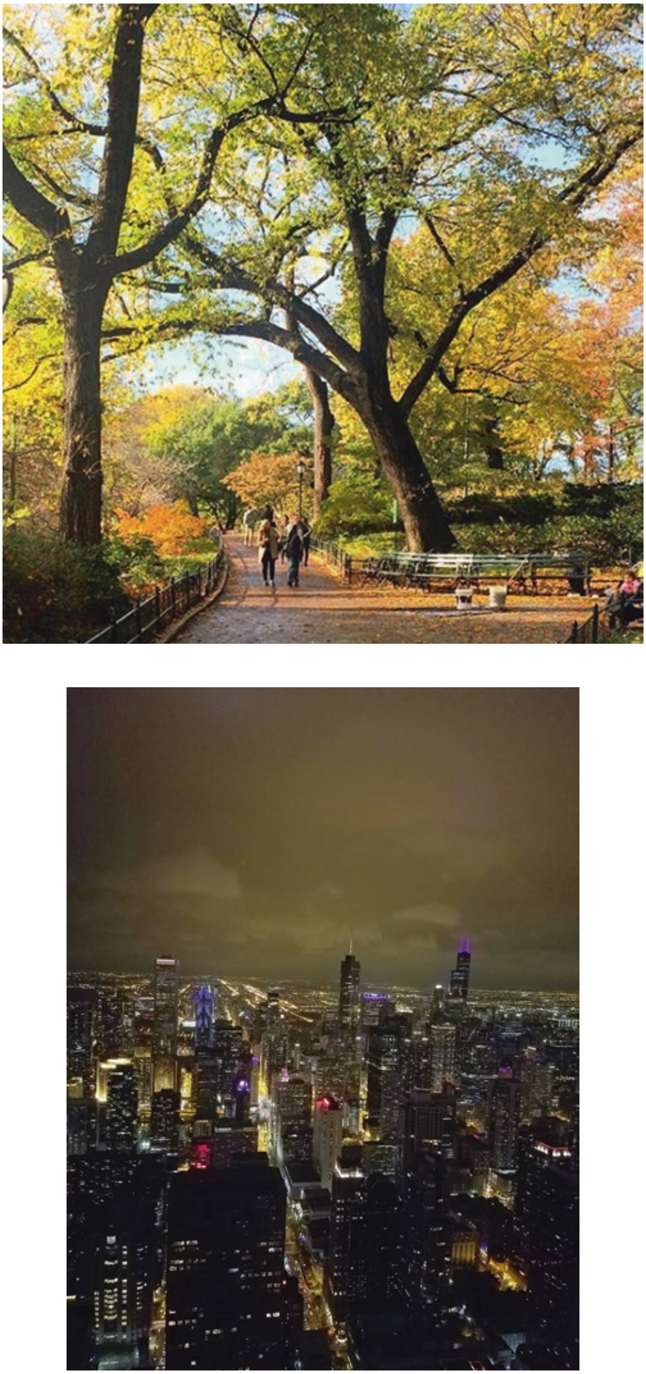

Fig. 1.2 (**a**) New York City by day and (**b**) Chicago by night (Image sources courtesy of: (**a**) Jennifer Kinder; (**b**) Helen Marie Havnaer)

synchronizes well with E. P. Odum's definition of ecology as "the study of the relationships between structure and function in nature" [6] and provides strong rationale for applying the science of ecology to the study of cities as well, including how human behavior as studied by social scientists and ecosystem behavior as studied by natural scientists are linked and, together, comprise the urban ecosystem.

1.1.2 Ecology and Ecosystem

Oekologie comes from the Greek word *logia* meaning the study of *oikos*, the hearth or home. In 1866 Ernest Haeckel coined the term ecology and defined it as follows:

> By *ecology* we mean the body of knowledge concerning the economy of nature – the investigation of the total relations of the animal both to its organic and inorganic environment; including above all, its friendly and inimical relations with those animals and plants with which it comes directly or indirectly into contact – in a word ecology is the study of the complex interrelations referred to by Darwin as the conditions of the struggle for existence [7].

He refined this to "the comprehensive science of the relationship of the organism to the environment" [8]. Building on this concept, Tansley in 1935 first used the word *ecosystem* defining it as "the whole system (in the sense of physics) including not only the organism-complex but also the whole complex of physical factors forming what we call the environment of the biome—the habitat factors in the widest sense," including not just the biosphere but also the lithosphere, the hydrosphere, and the atmosphere [9]. Andrewartha and Birch's 1954 definition of ecology as the "scientific study of the distribution and abundance of organisms" was, for a long time, the most commonly used definition, popularized by Krebs textbook of the same name [10, 11]. In the middle of the last century, ecology, and its definition, has moved away from only a taxonomic and accounting perspective that looks primarily at structure to one that emphasizes analysis of the functional interactions between and among the biotic and abiotic components of an ecosystem. E. P. Odum's definition cited above [6] was simplified by his brother H. T. Odum to "the study of environmental systems" [12, 13]. Together the Odums are considered the fathers of systems and ecosystem ecology, a perspective that is ideal for studying a system as complicated as a city. From the work of these earlier ecologists, we have derived a definition of *urban ecology* as the study of the biotic and abiotic structure and function of cities.

But what IS ecological structure versus ecological function? Urban ecological structure is the "nouns" of the environment, the number, size, composition, and nature of the components, and is comprised of abiotic and biotic components. The latter include all living things in a city—people, plants, squirrels, birds, insects, and, yes, even rats. The abiotic components are the nonliving things, like the water and air that flow through the city; quantity and nature of the nonorganic chemicals such as mercury, lead, and ozone; and, of course, the buildings, streets, sewer trunk lines, and more. These components together make up the *structure* of the urban ecosystem. Understanding how they interrelate, or *function*, is the verbs and includes how species have adapted to or evolved in the urban environment. Collectively these are the interesting challenges for an urban ecologist. Due to the massive ecosystem changes that have occurred so rapidly since the onset of industrialization, urban ecosystems provide opportunities for the study of dynamic ecology that do not exist in systems that have been stable and undisturbed over a long period of time. Learning more about the response of plants, animals, and humans to these changes may provide society with many insights into how to create more sustainable and livable urban habitat.

1.1.3 Metabolism

The most important functions of ecosystems are related to metabolism, which is defined as "the chemical and physical processes by which a living thing uses food for energy and growth" (https://dictionary.cambridge.org/us/dictionary/english/metabolism) or as (1) "the sum of the physical and chemical processes in an organism by which its material substance is produced, maintained, and destroyed, and by which energy is made available" or (2) as "any basic process of organic functioning or operating; *changes in the country's economic metabolism*," for example (https://www.dictionary.com/browse/metabolism). We can see, therefore, that metabolism refers both to biological/physiological processes and social processes. The concept of metabolism has been well developed, indeed is central, in physiology and ecosystem studies [14, 15].

1.2 Why Study Urban Ecology?

1.2.1 Global Urbanization: Social and Environmental Effects

At the dawn of the twenty-first century, over half of the world's population lived in urban agglomerations. This growth has resulted in magnificent human living areas but also increasingly degraded human habitats, as well as the loss of the natural ecological systems upon which all life, including human, depends. Urban slums are the largest growing human habitat globally, but even an economic boomtown such as Seattle, Washington, home of Boeing, Microsoft, Starbucks, and Amazon.com, which is often touted as an example of a "green" city in terms of its environmentally friendly culture, vision, and planning, ironically finds itself looking out over the once biologically rich Puget Sound where now the magnificent orca whales are expected to disappear in the next 30 years, and like its west coast neighbors of

Portland, Oregon, San Francisco and Los Angeles, California, struggles to accommodate large tent enclaves of homeless people living under freeways and bridges, in parks, etc.

Most “natural” ecosystems today are dominated by human activity either directly or indirectly, and many are increasingly stressed by human influence, in particular by the extraction of resources and the generation and deposition of wastes to sustain the consumption demands of our increasingly urbanized world. In the summer of 2010 alone, this included the destruction of aquatic life in the Gulf of Mexico due to the Deepwater Horizon oil drilling disaster; forests of the Caucasus Mountains burned by acid rain; peat bogs on fire outside Moscow, Russia; and flooding in Pakistan covering an area the size of Italy. These are only a few of the thousands of examples of alterations to once anthropogenically undisturbed naturally functioning environments caused by urban demands for resources, however distant. Urban environmental problems may be the largest we face globally in the decades to come, so this topic will grow in importance. Qi Ye, professor at Tsinghua University, Beijing, China, states, “Urban environmental quality is *the* largest problem facing China today” (*personal communication*).

The world is facing unprecedented population growth. As of 2018 over half (55%) of the global human population of 7.6 billion lived in cities, and the United Nations (UN) projects that number to reach 68% by 2050 [16]. The ecological effects are already considerable and will only increase in the future, both in cities where people need clean air, clean water, nutritious food, and energy and in the rural environment that provides many of these amenities to city dwellers. Estimates of future global population growth vary between a maximum of 8 billion before 2040, due to limited resources, according to Randers, or possibly to a much higher number, 11.3 billion, by year 2210, as projected by Fuller and Romer [17, 18]. Whatever the number, that is a lot of people, and there is general agreement among demographers that most of that growth will occur in urban areas. The UN projects that the 20 most urbanized cities in 2100 will be found in what is now considered the developing world, in the southern hemisphere (Table 1.2). In 2018 Tokyo was the largest city, followed by New Delhi, Shanghai, Mexico City, and Sao Paolo. What this means is that more and more people will need clean water and clean air, in places that already cannot provide for such. In 2018 30% of the global urban population was living in urban slums, defined as settlements or neighborhoods of a city that lack the basic living conditions for their inhabitants, like running water, permanent housing structures, sewage removal, etc. (UN World Cities). Some of the largest urban slums include Khayelitsha in Cape Town, South Africa; Kibera in Nairobi, Kenya; and Dharavi in Mumbai, India (for photos, see Bendicksen [19]). The World Health Organization reports that two million people a year die from outdoor air pollution while another four million are killed by indoor air pollution produced by their cooking stoves. In addition to air quality effects, intensified urban growth will have consequences on various systems, including agriculture, climate, fresh water, energy supplies, and wildlife, to name just a few.

Table 1.2 Largest cities in 2100 based on population projections of the United Nations Department of Economic and Social Affairs—population division world urbanization prospects—The 2011 revision. United Nations, New York

Rank	City	Estimated population
1	Lagos, Nigeria	88,344,661
2	Kinshasa, Democratic Republic of Congo	83,493,793
3	Dar es Salaam, United Republic of Tanzania	73,678,022
4	Mumbai, India	67,239,804
5	Delhi, India	57,334,134
6	Khartoum, Sudan	56,594,472
7	Niamey, Niger	56,149,130
8	Dhaka, Bangladesh	54,249,845
9	Kolkata, India	52,395,315
10	Kabul, Afghanistan	50,269,659
11	Karachi, Pakistan	49,055,566
12	Nairobi, Kenya	46,661,254
13	Lilongwe, Malawi	41,379,375
14	Blantyre City, Malawi	40,910,732
15	Cairo, Egypt	40,542,502
16	Kampala, Uganda	40,136,219
17	Manila, Philippines	39,959,024
18	Lusaka, Zambia	37,740,826
19	Mogadishu, Somalia	36,371,702
20	Addis Ababa, Ethiopia	35,820,348

1.2.2 The Need for Informed Solutions to Future Challenges

In the January 3, 2010, issue of *The New York Times'* Education Life supplement, the feature article was entitled "The Utility Degree: 10 master's degrees for the new world order" of which number 4 was "Urban Environment: Sustainability Comes of Age" by Henry Fountain [20]. Indeed, over the last two decades, we have witnessed the shift from the historical focus of ecological research away from wildlands to those environments where the majority of people reside and from which the majority of environmental problems emanate. Ecology, once primarily the domain of biologists who focused on the earth's wild lands, has more recently identified cities as rich ground for exploring ecological theory. Urban ecology seeks to understand the connections between human well-being and the environmental systems that support human life. Increasingly urban planners, educators, and decision-makers look to urban ecology for help in designing a more sustainable, resilient, or "green" urban future. Some of the questions being asked are (a) Can we provide reliable and environmentally benign energy sources to support urban metabolism? (b) How do we choose among alternative urban land uses (e.g., an urban forest versus a community vegetable garden, or neighborhood solar installation, a water treatment wetland vs.

low-income housing, or a neighborhood park, to name a few)? (c) How do we evaluate the potential effect of each on the city's energy budget, water or air quality, and citizens' quality of life? (d) How do we engage and support citizens in activities that will enhance urban metabolism that encourages urban flora and fauna, for instance, or that will nurture enhancement of ecosystem services, biodiversity, etc.?

As cities have developed, people have become increasingly separated from the rural or natural environments that provide the city and themselves with the resources required for survival. Interestingly the discipline of ecology over its history has perpetrated a separation of humans from nature by focusing on wild life and wild systems rather than those in which human settlement, human management, and human intervention play a primary role. European ecologists took the early lead in studying ecology in cities. Today the US National Science Foundation supports coupled nature-human systems research and a new emphasis in ecology, on biophysical economics and ecological economics with their emphasis on industrial and natural energy flows, and on ecosystem services, ecosystem sustainability, and ecosystem resilience. These are attempts to reconnect people's understanding and appreciation of the importance of the biophysical world to sustain cities. Understanding this connection should help us teach generations to come how importantly the two are linked.

Furthermore, the emphasis on studying urban ecology from a systems perspective should lead to more informed decision-making when difficult choices that affect urbanites and their environment must be made. Ignorance may be bliss as the expression goes, but all too often costly decisions are made by urban dwellers, and the governments they elect, that are short sighted. Jay Forrester, in his 1961 book *Urban Dynamics*, pointed out how so many decisions in that era brought unintended negative consequences to many US cities, particularly those across the United States' "Rust Belt" that were in economic decline following closure of many industries [21]. He pointed out how decision-makers who lacked the training to think across multiple systems and evaluate whether a proposed solution would have long-term positive benefits for communities created larger problems. One such example, popular at the time, involved building low-income subsidized residential "projects" in inner cities. Not only did it create an inhumane environment for the people who lived there, causing crime and social distress, but it also drove investment away from the inner city and took up prime real estate that could have been used to build new industries that would have given people jobs and income, which are what they really needed in order to have quality of life, including good housing.

When you are finished with this book, we hope the systems perspective that we use throughout will have given you a better idea of how to integrate the biophysical systems of meteorology, hydrology, and energy with social science perspectives such as psychological perception, decision-making, and behaviors that characterize our human social systems. Both perspectives influence how we create and manage the built environment and contribute to what we buy and how we dispose of it. These decisions in turn affect the biophysical resources on which we depend for quality of life (Fig. 1.3). If we can understand the interplay among all of these factors as they change with urbanization, we will more likely be able to mitigate the

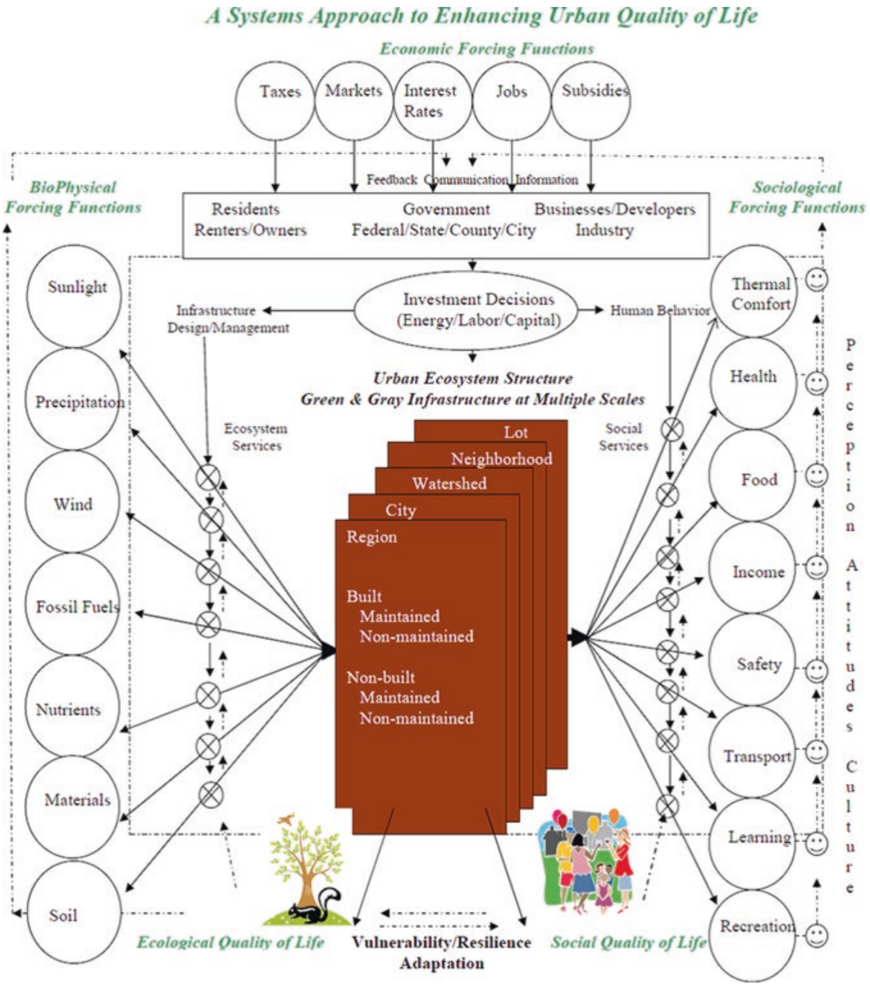

Fig. 1.3 A diagrammatic systems model of the social-ecological factors that determine the metabolism of an urban ecosystem and hence quality of both sociological and ecological life. (Drawing source: M. Hall)

bad effects of urbanization and promote more sustainable solutions that will support urban resilience.

Finally, it is a good thing to study urban ecology simply because it is a good thing to be an educated person, to understand how the world around you works. Ecology, like chemistry, biology, and physics, is a science that contributes to that understanding. The authors of this book believe that understanding the ecology of the world around you, including cities, is just as important as art history or music appreciation for developing a full and interesting life. From earlier ecological studies focused on "wild"[1] systems, we have already learned a great deal about how ecosystems are organized and maintained that is equally applicable to a city. Cities in turn offer interesting hot houses and readily accessible ecosystems for observation and discovery as species evolve in new habitats; trees and people are stressed by the urban heat island; soils are compacted, but plants still find a way to survive, etc. New discoveries can lead to novel inventions. But urban ecology also offers one the opportunity to explore the tight connections between the biophysical world and the socioeconomic world that are critically important to designing our future. Even if you do not go on to be a famous ecologist, the ability to think broadly and critically about important environmental and social issues will benefit you and those around you both materially and spiritually.

1.3 Analytical Approaches

Studies in ecology often use some common currency, such as energy or matter, to trace the flows among ecosystem components and to explore their sensitivity to variation of different inputs like sunlight, precipitation, nutrients, and energy, or to variation in, for example, predation, exploitation, and population growth. This book is organized to look at the principal subsystems of the urban ecosystem and the flows particular to each of them that support urban quality of life. These include the hydrological system, the climate system, the atmospheric system, the energy system, the nutrient cycling system, the material cycling system, the biological system, the economic system, and the sociological system. How human decision-making affects these flows is a critical component in understanding urban ecosystem structure *and* function.

1.3.1 A Systems Ecology Approach

Although there is now much attention in the field of ecology given to studies of "*coupled* human/nature systems," they tend to examine human systems only as sources of alterations to the natural world. In contrast, from a *systems ecology* perspective, humans are included as *part of* nature, the same as fish, bears, and turtles. Their metabolic requirements, their controls on ecosystem flows of materials and dollars, can be measured and modeled in the same way that these factors are quantified for other organisms. Within the systems ecology perspective, social science research is also needed to understand the various factors that drive human choices and how we perceive environmental risks and impacts that frame those choices. Linking the social and natural sciences to assess fully the human role in ecosystem

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[1] "Wild" is used here instead of "natural" systems, since it is the view of the authors that people are part of nature and that what they do is natural.

functioning is critical. Ecology, and in particular the modeling perspective of systems ecology put forth by H. T. Odum, offers the perspective and analytical tools to do this most effectively [13].

Traditionally people have applied the word ecosystem to natural communities of organisms living in environments comprised of varying climatic and geologic conditions that together produce very different structures such as a marsh, a forest, a desert, or a pond. Because ecology is usually considered a branch of biology, the general science that studies living organisms, ecological studies have focused on the biology of these systems. This is unfortunate since ecology should study the entire system and, therefore, encompass physics, chemistry, hydrology, and other nonbiological components. On the other hand, due to the presence of humans and the institutions they have created to regulate urban life, the study of urban systems traditionally has been the domain primarily of social scientists. However, humans are as much a part of nature as any other organism, including in their dependence upon natural ecosystems for resources and processing of their wastes. Cities, although of very different physical structure from more "natural" systems, due primarily to technologies fueled by the age of oil, exhibit the same functional relations between the biotic and abiotic components. Organisms, including humans, can be studied at many different levels, e.g., from proteins and nucleic acids to their role in ecosystems to the biosphere, and from many different disciplines, e.g., biology, physiology, or psychology. Ecology, because of the complexity of ecosystems, must be multidisciplinary, or better yet, interdisciplinary, and it should be about relations among and of parts. It should incorporate geology, geography, biogeochemistry, hydrology, and psychology, to name a few essential disciplines. Using a systems ecology approach, therefore, to understand the relations among the diverse components of the urban ecosystem is more appropriate than studies by separate disciplines and highly necessary if we are going to create sustainable urban communities for today and tomorrow.

However, the field of ecology has long ignored the human component of ecosystems, and sociologists have long ignored the biophysical underpinnings of human activity and behavior. We attempt, therefore, in this book to expand ecology into sociology-ecology, which is a systems perspective. Leaders in the scientific community, particularly in Europe, and more recently the United States, have been pushing natural and social scientists to engage in social-ecological research. The challenge is getting biophysical scientists to interact effectively with social scientists and vice versa [22]. Because humans are dependent on both social and ecological systems and cities are very much human-dominated ecosystems [12, 23–25], it is essential to explore concepts, methods, and language that combine approaches. Haberl and others identified four general themes that are central to social-ecological research that make for truly interdisciplinary engagement: social-ecological metabolism, land use and landscapes, governance, and communication [26]. Throughout this book we build upon these four pillars, with social-ecological metabolism as the integrative conceptual "glue." They include conflicts and trade-offs over land use and urban landscape and the needs and constraints of government and citizens to find sustainable, cost-effective solutions to a variety of urban social-ecological issues. Students will be introduced via accompanying labs to how to make models (in the form of quantitative diagrams) of the processes fundamental to assessing metabolism. This kind of integrative activity can help assess and communicate the implications of proposed management decisions and inform decision-making dialogue.

From a practical perspective let's consider some examples from cities around the world where the lack of a systems perspective nor understanding of societal metabolism produced unintended results. Forrester calls these the counterintuitive results, or unintended consequences of policies prescribed without the benefit of systems thinking, i.e., considering the response of the system at large [21]. He uses as example the building of inner city high-rise low-income housing developments that prevailed in the United States during the 1960s in places like Chicago and the Bronx of New York, most of which have now been torn down. Meant to provide shelter, they in fact became breeding grounds of crime while removing valuable urban land from other kinds of development that might have provided jobs for the urban un- and underemployed. They contributed to a decreased tax base, less funding for city schools, overly taxed police forces, and general urban decline in our center cities. Another example is that of the redlining policies instituted during the Roosevelt era. Intended to jumpstart housing construction and remodeling investment in the United States, the program guaranteed bank loans at different percentages of the total loan depending on whether a property was located inside a green, blue, yellow, or redline region delineated by local authorities to designate investment "risk" levels. The legacy of those policies left cities across America, but particularly in the Northeastern United States, right up until today with the equivalent of bombed-out inner city neighborhoods, full of boarded up, vacant houses, in advanced stages of decline, because no funds for reinvestment were made available to people who lived there. A third example is the building of superlane highways across the United States and through urban centers. Originally foreseen as a boon to commerce, it is instead another example of a policy that did not consider all of the potential effects on society. This program of the Eisenhower era dissected major US cities with noisy overhead highways that accelerated both urban flight and urban blight by making it easier for people who worked downtown to commute from the suburbs, thus taking their income with them. The City of Boston, MA, in 2007 completed the 22 billion dollar "Big Dig" project burying the overhead interstate highway to reconnect the inner city to its waterfront and North End neighborhoods, enhancing both the social and economic metabolism of the city, but at huge public expense due to lack of systems thinking years earlier.

In contrast former Curitiba, Brazil, Mayor Jaime Lerner was a systems thinker. He recognized that livelihood comes first. He implemented, among many innovative urban programs, a system that provided underemployed families with fresh fruits and vegetables from nearby farms, in exchange for recyclables they collected from city streets. The proceeds from the recycled materials went back to the farmers to pay for the fruits and vegetables. As a consequence, the inner city is garbage-free and full of vitality. Sprawl is not an issue because the city is such a desirable habitat, and farmland is preserved so that fresh food can still be produced nearby [27]. Too often bandages applied to urban wounds exacerbate the problem, whereas correct understanding of the ecology and economics of a system can result in enhanced ecosystem functioning, of the kind seen in Curitiba.

1.3.2 Social-Ecological Metabolism

The reason that we have chosen social-ecological metabolism as our conceptual analytical paradigm for the study of urban ecology is threefold:

1. All processes in which there is motion, which is to say essentially everything that happens in a city, are of thermodynamic necessity associated with, and dependent upon, the flow and transfer of energy, that is, energy use metabolism, which is composed of *production*, capture or generation of energy, and *respiration* or consumption of it (see Chap. 2). By-products or metabolites include pollutants of concern: sewage, CO2, combustion particulates, and excess nutrients (see Chaps. 6, 8, 9, 10). Thus, metabolism as a concept integrates many city processes and is particularly relevant to a study that evaluates the impacts of changing land use and land cover as a contributor to future sustainability.
2. Metabolism is a means of showing the connectivity, relative importance, and to some degree similarity of all city processes, whether strictly biophysical or social. Social-ecological metabolism has been shown to have great power in understanding cities [26, 28–31]. Haberl and others, especially, have shown that metabolism is not conceptually separate from a social perspective of cities but rather central to it [26]. Human decision-making is in a sense a means of directing, controlling, or enhancing metabolism. Even money can be considered as a lien on energy, for without energy flow money has no value. In the United States in 2015, about 6 mJ (million Joules of energy) were required for each dollar of economic activity [32]. Because cities today almost invariably support far more respiration than production, of both food and fossil energy, they are invariably dependent upon external sources of production [33].
3. The third reason to focus on urban metabolism is that the most urban energy sources for a city's metabolism are derived from fossil fuels, especially oil, coal, and natural gas, with oil being especially important for the transportation necessary to bring the resources required for cities to the cities. These fuels are likely to become increasingly inaccessible through increasing price and actual physical shortage within the lifetimes of many who read this book [32, 34]. Most of the financial meltdown of the second half of 2008 has been attributed to the loss of discretionary income due to oil price increases in the previous 13 months [35]. We believe there is a strong possibility that oil price increases and the possibility of an actual shortage are critical issues that city leaders and residents must face, and it provides a strong rationale for developing an assessment of the relation between social-ecological flows and human activities that might allow for mitigation. Green infrastructure is being promoted in many climate/energy policy discussions as one form of mitigation.

1.4 Analytical Tools

There are many diagnostic and analytical tools used by ecologists to understand the relations between organisms and their environment. We will describe several of these here conceptually to prepare you to evaluate ecosystem structure and function, the relations between ecosystem components, and the requirements for sustainability. The first recommendation to you as a beginning ecologist is to simply observe and think about why certain components of an ecosystem are found where they are and how they are maintaining life. With both plants and animals, you may want to think about where they evolved and how, therefore, they can survive in the city. How do they get food, sunlight, and moisture? How do they influence the environment of other organisms and vice versa, or how do they alter or are altered by the biophysical environment in which they are found? These questions apply to humans equally.

1.4.1 Environmental Gradient Analysis

A more formal approach is to collect samples of organisms, for example, and evaluate the variation in your samples as a function of the different environmental factors present where you collected them. This approach is often called environmental gradient analysis, and each factor of interest can be considered an environmental gradient (something that varies from high to low), like concentrations of nutrients in stream water or the percent of canopy cover on an urban block. Gradient analysis begins with an assumption that an organism grows and produces best at the center of its ecological optimum or ecological gradient space, i.e., the environment it has evolved over time to take advantage of. Almost all biological organisms are controlled by temperature. As they encounter temperatures farther and farther away from their ecological optimum, they reach a threshold where their energy reserves are so low they cannot produce and another threshold where they cannot survive [36].

In urban ecology one means of looking at changes in organism abundance induced by urbanization is to do a study along a rural to urban gradient [37, 38]. If such a gradient includes on one end the type of environment that existed in the region prior to the advent of industrialization, the gradient replaces space for time, allowing us to see what may have existed ecologically in the region in times past. Soils, streams, vegetation, and the organisms that inhabit them change dramatically along such a gradient (Fig. 1.4). In contrast to a simple gradient of not developed to very developed landscape, i.e., the rural to urban gradient, it is more informative to assess species presence/absence, richness, or abundance along an environmental gradient. For example, you might assess these along a gradient of soil organic matter (from none to lots) or soil bulk density (loose to compacted), or nutrient availability (high to low). This is informative and important to urban sustainability. When soil organisms are missing in urban soils, there is a great economic cost to overcoming the deficiency either through the addition of organic matter often hauled

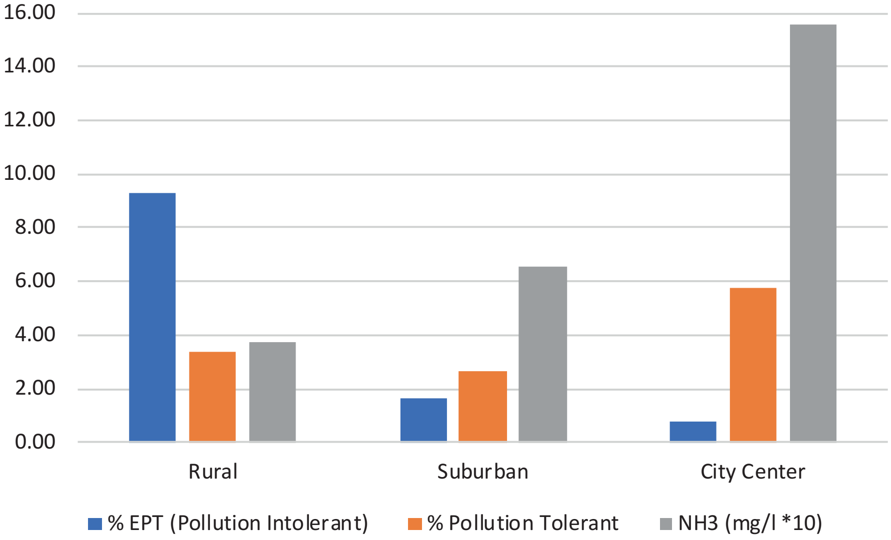

Fig. 1.4 Changes in stream ecosystem structure along a rural to urban gradient: percent of sample at each location (rural, suburban, inner city) that consists of pollution-intolerant (%EPT) versus pollution-tolerant benthic macroinvertebrate species. Note that concentrations along the environmental gradient of ammonia (NH_3) increase while the percent of pollution-intolerant species declines.

from far distant locations or removal of leaf litter for which there are no organisms to turn it back into soil. This is significant if we wish to maintain, for example, an urban forest that provides cooling and aesthetic relief to urban inhabitants. The costs of soil organism substitution may not be sustainable over a long period of time; hence an ecological study of this type allows us to assess how we might reconstitute urban soil communities to do the work required to sustain the forest in perpetuity.

1.4.2 Correlation Analysis

Another simple tool that can be used in such studies is to explore correlation between the samples you collect, such as numbers of organisms found at each site, and the measured values of different environmental factors such as perhaps temperature, soil pH, or number of cars passing in an hour, that you hypothesize exercise some control over the organism's distribution and abundance. The Pearson's correlation coefficient known as R^2 tells you the degree to which a dependent variable, for example the quantity of total phosphorous (TP) coming out of the New York City drinking watersheds, is correlated with the area of paved or impervious surfaces in the watersheds. In our example (Fig. 1.5) the R^2 equals 0.62, which means that 62%

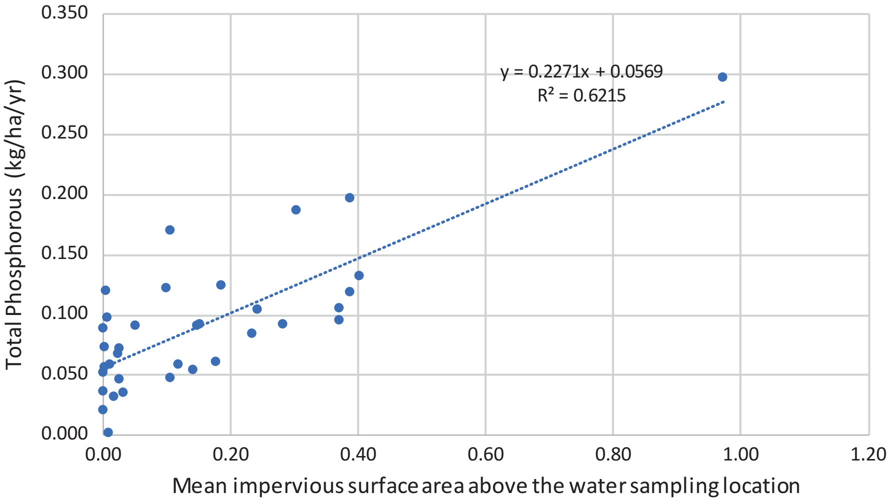

Fig. 1.5 Correlation between the dependent variable, the amount of total dissolved phosphorus (TDP) in New York City watershed stream samples, and the independent variable, the mean impervious surface (IS) in the area contributing runoff to each sampling location. Mean impervious surface is measured as the mean of the percentage of IS from the National Land Cover Dataset of 2002 in each 30 × 30 m cell of the total cells lying in the contributing area (Source: Myers and Hall [39])

of the variation in the measured TP values can be explained by the amount of impervious surface above each stream sampling point. An R^2 value of 0 would indicate that there is no correlation and a value of 1, perfect correlation. When graphed with the independent factor as a gradient on the x axis and the dependent factor on the y axis, an R^2 equal to 1.0 would be represented by a straight line at a 45° angle. This type of analysis can be taken a step further using a statistical analysis package to determine which of many factors together explain most of the variation in your sample. This is called multivariate stepwise regression analysis. R^2 in this instance tells us how much of the variation in our data is explained by each of the factors that are correlated with the quanity of the analyte observed. In the following equation from a study of land use nutrient export to streams in New York City's Catskill Mountains watersheds, stepwise regression analysis of the amount of total dissolved phosphorus (TDP) produced $R^2 = 0.77$ [40]. What that means is that 77% of the variation in the measured amounts of TDP in those streams can be explained by a combination of factors that include agricultural land use (AGR), quantity of impervious surfaces (MeanIS), parcel density defined as number of lots (ParDen), and the soil erodibility factor (Kfact) in combination:

$$\begin{aligned}\mathrm{TDP}(\mathrm{kg/ha/yr}) = 0.39889 + 0.22838(\mathrm{AGR}) + 0.21817(\mathrm{MeanIS})\\ -0.00451(\mathrm{ParDen}) - 1.54874(\mathrm{Kfact})\end{aligned} \tag{1.1}$$

Phosphorus and nitrogen in our drinking water need to be monitored and controlled. When applied to these and many other important indicators of unimpaired ecosystem functioning, this methodology allows us to see if and when urbanization or other human land uses might destroy the natural systems upon which cities are dependent for long-term sustainability, i.e., ecosystem services like clean unfiltered drinking water.

1.4.3 Footprint Analysis

An interesting way to think about whether the urban ecosystem is sustainable is to calculate the demand an urban area puts on a wider geographic area and the resources that the area provides, i.e., how much energy or any material must be extracted elsewhere to support the lifestyle of a home, a block, or the city itself? This is referred to as ecological footprint analysis [41]. Calculations for Vancouver BC in 2006 revealed an ecological footprint of 10,071,670 global hectares (gha) or 36 times the area of the city itself to support the city's metabolism [42]. Food production was the largest component (see Chap. 14).

1.4.4 Systems Flow Diagramming

A diagrammatic model, such as a systems flow diagram, is a highly useful analytical tool that helps us understand the function of different components of the urban environment. H.T. Odum, because of his interest in the circuit language of electrical systems, invented this type of diagram to track the changes in storages and flows of energy in an ecosystem [12]. Making such a diagram forces one to think about the most important components of a system in terms of energy and material flows and the controls on those flows. The act of diagramming also helps us understand how these elements connect and interact. Eventually, by determining the inputs, transformations, and outputs of energy or materials of the city, we can build computer models to calculate changes in ecosystem stocks and flows if one of the inputs is changed, such as alteration of consumption patterns or implementation of methods to reuse waste material (see Chap. 10). Zucchetto created one of the first urban systems flow diagrams (Fig. 1.6) for the city of Miami, Florida [43]. He diagrammed and calculated the flows and storages of land, energy, and materials, natural and man-made; how they entered urban production activities, like those of development and industry; the feedbacks produced; the wastes created; and the controls on these flows by government and individuals, not unlike the conceptual model illustrated in Fig. 1.3. This diagram might need alteration to reflect the metabolism of modern corporate cities (see Chap. 5).

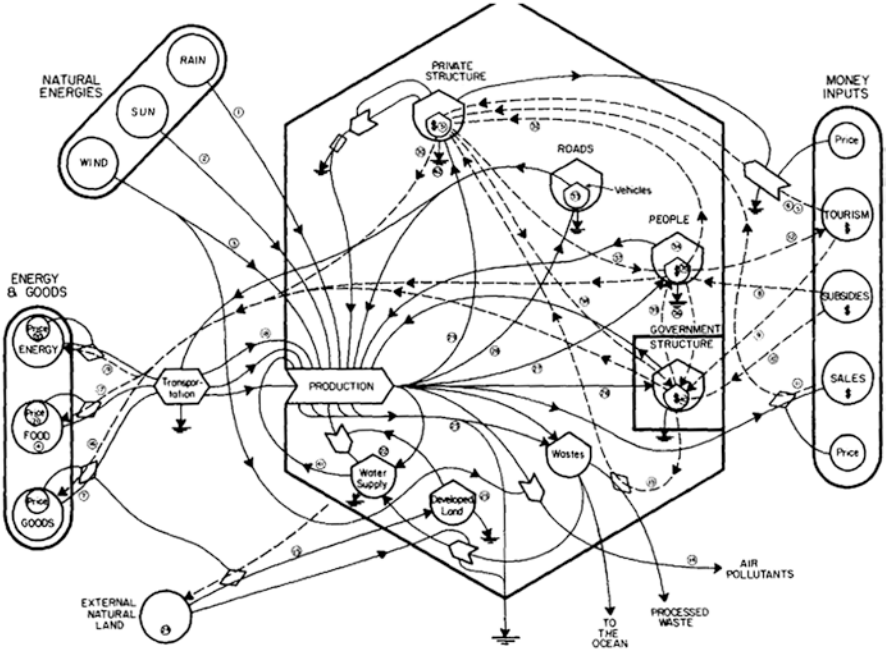

Fig. 1.6 Systems flow diagram of Miami, Florida (Source: Zucchetto [43])

1.4.5 Energy Return on Investment (EROI) Analysis

To understand the enormous dependence of the city on energy and whether substitution of alternative fuels, like wind, solar, and biofuels for traditional fossil fuel energy will allow cities to keep functioning as they currently do, we can evaluate the per unit energy return on unit of energy invested (EROI) to extract each unit of energy required for our current lifestyle. Around the world advocates of green fuels, green infrastructure (GI), and green jobs have proposed various nature-based technologies as means to revitalize the economies of cities [44]. While the benefits of many of these have been investigated, the trade-offs between them have not. Many are very energy intensive to install and to maintain. In limited urban space, one type of GI may preclude others. Hall and others evaluated the energy costs and benefits of three neighborhood greening strategies—tree planting, rooftop solar thermal (hot water heating) systems, and urban food production [45]. They found that solar thermal would yield an EROI twice that of urban food production and over three times that of an urban forest (Table 1.3).

Table 1.3 Annual energy (GJ) cost and benefit derived for three proposed urban greening solutions for the Near Westside Neighborhood of Syracuse, New York

Greening strategy	Cost	Benefit	Net energy	EROI
*Tree planting	20.5	21.83	1.33	1.06:1
**Solar thermal	103	370	267	3.6:1
***Food production	170	320	150	1.9:1

*Energy costs equal those of implementation and maintenance; energetic benefits for trees are those related to reduced stormwater flow, hence reduced costs of sewage treatment (pumping and chemicals) plus reduced air conditioning costs to homes (see Chap. 8); ** energetic benefits from solar thermal are the reduction in electric energy consumption to heat water, and *** energetic benefits from food production are calories delivered to citizens' diets. All are calculated in gigajoules.

1.4.6 Emergy Analysis

Finally, an extension of systems diagramming, and energy analysis, is emergy analysis, which calculates the amount of embodied energy in each material good used by society including both industrial energy (e.g., fossil fuels) and natural energies (including sunlight, rain, and so on) and how that is transformed through use [46]. Embodied energy is all the energy that was consumed to produce something. It can include the energetic cost of extraction of the raw materials, the energetic cost of the transformation of those materials into some usable product, the transportation energy cost of moving the product to market, etc. Examples of emergy analyses are those used to calculate the urban socioeconomic metabolism for Beijing, China, and Taipei, Taiwan [47–49]. Other examples are given in Chaps. 10 and 15.

Each of these types of analysis is designed to help society evaluate the effects of our lifestyle, or culture, on the natural environment, and evaluate what is sustainable and what is not.

1.5 Conclusion

The study of urban ecology is critical in the face of an increasingly urbanized world. Cities and Nations are faced with degradation of both the natural systems upon which we depend and the urban habitats where we live. The scientific methods described in this introductory chapter provide rational tested tools for understanding the world we live in, i.e. the structure and function of the urban ecosystem. They provide means to evaluate the trade-offs between alternative choices that we must consider as we strive to preserve both environmental and social quality of life. The scientific method will be encouraged throughout this book as a way to avoid what appear to be helpful, but sometimes just expedient, policies that are often based on intuition or culturally induced perception, rather than data-based analyses. As we have seen from the few examples set forth here, policies to fix one problem, though often well-intended, may in fact exacerbate another, resulting in undesirable, but unforeseen consequences. Analyses done first to understand the sensitivity of the various components of the ecosystem to change, and second to understand potential feedbacks of various actions, are more likely to lead to solutions to urban problems that can produce lasting positive results, not waste money nor energy, and hopefully contribute to more sustainable and resilient cities.

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Chapter 2
Urban Ecology from a Biophysical and Systems Perspective

Charles A. S. Hall

Abstract Cities are a common and natural characteristic of both nature and human cultures over the last 10,000 years. Ecologically, both natural and human cities are regions of concentrated animal life, intense energy consumption (respiration, or R), and concentrated material accumulations and flows. They require much larger regions of net production (P) outside of the city to generate the food and other resources used within the urban area and large amounts of auxiliary energy to move that food and other requirements into the city and to remove wastes. There are many parallels between natural ecosystems and cities. Both contain abiotic (rocks, water, minerals, nutrient, houses) and biotic (trees, plants, animals) structure. For example, forested ecosystems have developed soils (abiotic structure) that allow for trees (biotic structure) to capture solar energy and feed energy to the rest of the ecosystem, including soils. This energy is essential for constructing the structure, and the structure is essential for maintaining the ability of the system to continue to capture and utilize incoming solar energy as well as to capture and hold water and recycle wastes. This chapter gives various examples of how urban ecosystems are like natural ecosystems in both structure and function and concludes that because humans are part of the biosphere, cities are really natural systems. It also concludes that the principal distinction between pre-Neolithic (Stone Age) human societies and Neolithic ones, or between Neolithic societies and modern industrial societies, is the amount of energy required to create and maintain the incredible infrastructure of modern cities. Modern urban areas have per capita GDP, energy consumption, and greenhouse gas emissions that are 2–3 orders of magnitude higher than subsidence-based populations in poorer countries. This suggests that urbanization is not a solution for resource scarcity-related problems in the twenty-first century.

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2.1 Introduction

Cities are an obvious and long-standing attribute of the contemporary landscape. Characteristic urban areas (i.e., a high degree of semi-permanent concentration of humans, social stratification, monumental architecture, large public works projects) first became established about 5000 years ago [1, 2]. The development of the first cities coincides with what we call civilization. This has also been called state formation and complex social organization. The first cities developed mostly in coastal zones and lower river valleys and were related to the dramatic increase in the biological productivity of coastal margins following the stabilization of sea level at the end of the last glaciation. This productivity provided an energy subsidy that allowed humans to make the leap from village/farming organization to much larger urban areas. Urban areas represent the greatest difference between "nature," that is, the world as it is untouched by humans and the world as transformed by humans. They are more abundant and larger now than ever. There are over 500 cities with greater than one million inhabitants, and much of the world is increasingly dominated by "megacities" of 10 million or more people. Many environmentalists are repelled by cities and support a desire for humanity to "go back to nature" and enter a simpler, supposedly less impactful and more natural lifestyle (e.g., [3, 4]). But are cities unnatural? Do we find cities in nature? How are they similar to human cities and how are they different? How do we even think about cities as ecological entities? We will try to answer these questions as we examine the role and activity of human cities in history and their relation to energy use.

How Should We Think About Cities?

It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.
...

John Godfrey Saxe (1816–1887)

There is a wonderful old story from India about six learned but blind men who were taken to an elephant, with which they were not familiar, and asked to describe it. One felt his side and said an elephant was like a wall, another felt the trunk and said an elephant was like a snake, another felt the knee and thought an elephant was like a tree, and so on. In other words, an elephant was many different things to people who experience it differently or have different perspectives, but in fact the elephant is all these things and more. Likewise, cities are simultaneously many different things depending upon the way different people experience it or interpret what they experience based on their background. Thus, cities may be considered, as analyzed in other chapters, as historical, demographic, geographical, cultural, or economic entities, depending upon the observations and backgrounds of the person doing the description. Most fundamentally, cities can be viewed as both social and biophysical entities. This chapter is about the biophysical properties and characteristics of cities, and the next chapter focuses on the social perspective. We think the biophysical properties must be considered first, as all of the other properties depend to at least some degree on them, for it is usually these properties that determine where cities are, what their economy is about, and ultimately the way people think about them. Reflecting these biophysical properties, Rees [5] argues that modern industrial society and modern cities are inherently unsustainable and from an energy standpoint that "cities are self-organizing far-from-equilibrium dissipative structures whose self-organization is utterly dependent on access to abundant energy and material resources."

The biophysical properties of a city include its location on the planet, its geographical setting, its climate and soils, its geomorphology, its relation to rivers and oceans, and its access to the physical resources that may impact it (e.g., floods, hurricanes, fires) and needed to support it, including food, water, and energy (Fig. 2.1). These resources may be from local or neighboring regions or they may be obtained through trade from more distant lands, but they are all essential. All of these characteristics have a great deal to do with how successful cities are as they develop, and sometimes degrade, over time. Cities throughout history have had higher area-based rates of energy and material consumption, but modern urban areas have dramatically higher rates of consumption that are orders of magnitude greater than preindustrial cities [7].

2.1.1 Geography

We start with a consideration of the geographical setting of cities. The initial development of cities all occurred in resource-rich areas that provided abundant natural resources and adjacent to water that provided cheap and far-reaching transport routes [8]. For example, most of the world's largest cities (Tokyo, Mumbai, Shanghai, Manila, New York, London) are located on estuaries where there are protective harbors and easy access to sea routes. These coastal areas also had abundant natural resources, for example, fisheries. Most original settlements on the East Coast of the United States were coastal such as Savannah, Charleston, New York, and Boston. In addition, there is a chain of cities (Augusta, Richmond, Washington, Baltimore, Philadelphia, etc.) that are located at the *fall line*, where the Piedmont region meets the coastal plain, where ocean-going ships had to stop and be unloaded for further transport of goods inland because the rivers at this point became unnavigable. These were also regions of abundant water power because of the steep drop in the rivers at the fall line. George Washington, originally a surveyor, is usually considered the father of East-West transportation as he put forth the idea of a series of canals to take goods across the fall line of the "Potowmack" River, eventually connecting to Ohio. In all of these situations, energy is key. Transport by boat using river flow or wind required much less energy and was much cheaper than by ox cart,

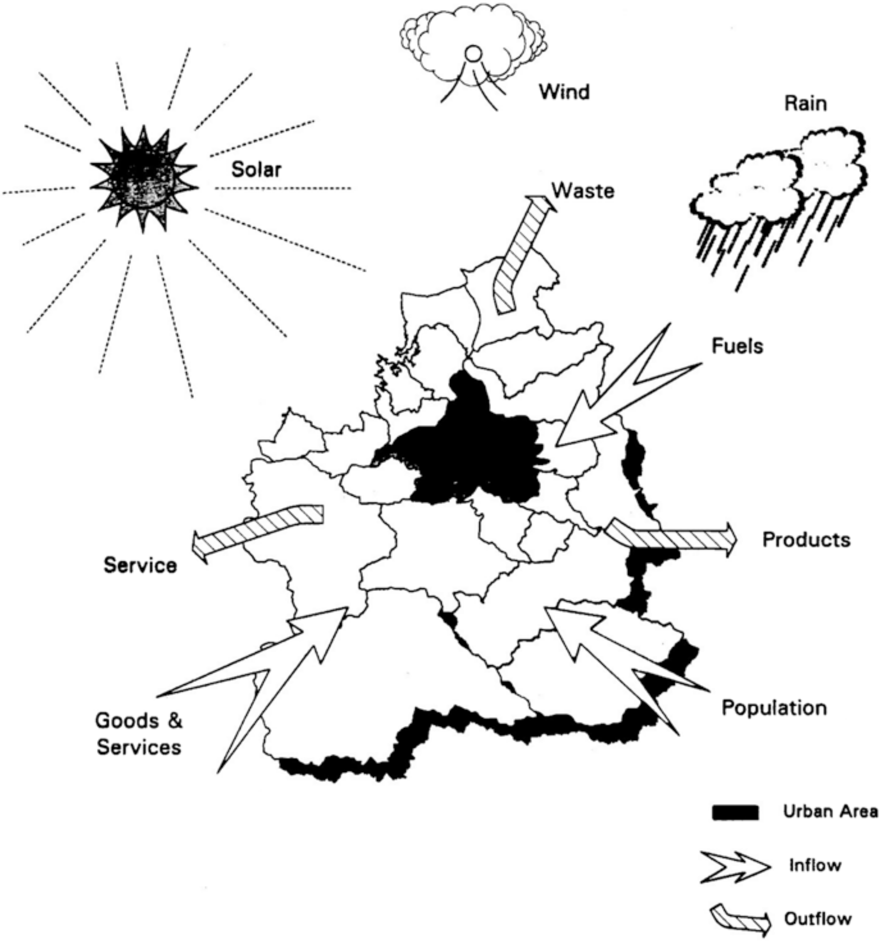

Fig. 2.1 An "ecological" view of a modern city (Taipei, Taiwan) showing the flow of materials and energy in and out of the city. (From Huang [6], with permission of Elsevier)

and obviously with horses or oxen, it is of great importance to avoid as many hills as possible. Syracuse, New York, for example, is located at the intersection of relatively low elevation North-South and East-West corridors (now holding interstate highways) (Fig. 2.2). Cottrell [9] writes of the importance of river flows bringing lumber and food produced upstream down to cities at the mouth of rivers.

2.1.2 *Climate and Fertility*

Humans seem to be adaptable to all but the most extreme of Earth's climates, including hot and humid tropical environments (Lagos, Singapore, Mumbai) and seasonally frigid northern climates (Stockholm, St. Petersburg, Toronto). Probably the

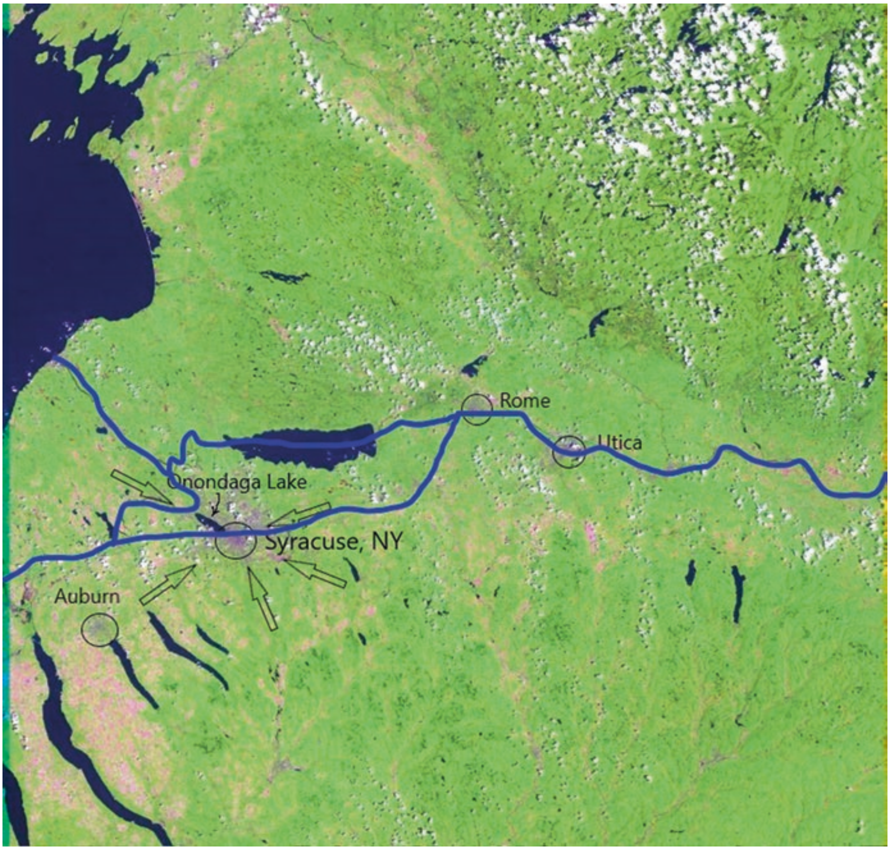

Fig. 2.2 Satellite view of Syracuse, New York (circled), and its surroundings. One can see Onondaga Lake that once provided many fish for the early human inhabitants. The relatively low-lying flat lands in valleys to the East and West, North and South, along with the abundant waterways (indicated in blue), allowed relatively low energy-requiring transportation. Interstate highways currently follow these earlier routes. Other cities, Rochester to the east, Rome, Utica, and Albany to the west (all indicated by purple), are spread out at more or less regular intervals within a much larger landscape of forest (green) and agricultural production (pink) necessary to sustain the centers of consumption. Arrows show proximity of production input areas to supply the city with food, fuel, and fiber

main way that climate impacts people is by the fact that high temperature limits the physiological ability of humans to work because of overheating. A Swedish lumberjack can cut perhaps three times more timber per day than his Malay counterpart, but not if you take the Swede to Malaysia where, once he acclimates, he can cut only about the same amount as the Malay [10]. On the other hand, a tropical forester or farmer has roughly 12 h of daylight a day to work regardless of season, where the Swede has 16 h in the summer but only 8 in the winter. Obviously, the middle of the day is a tough time to work in the tropics, so many farmers and shopkeepers in the tropics get up early, take a nap in the middle of the day, and then work again in the later afternoon.

More important than temperature is the productivity or fertility of the surrounding region, which depends on various things, including the amount and distribution of rainfall, the temperature and its annual pattern, day length, and of course soil fertility. Day length seems to be surprisingly important and appears to be an important determinant of the difference in agricultural productivity in temperate vs. tropical regions. The production of maize (called corn in the United States) is about four times higher per hectare per year in temperate regions compared to the tropics because during the growing season you have twice the daylight hours in a day where net production is positive compared to night. In the tropics, the day-night ratio is always close to 1:1 [5]. Soil fertility varies widely over the world. In general, newer soils are more fertile and older soils less so because rain has washed out many nutrients. New soils tend to be found in regions that have been glaciated, near volcanoes, and, especially, where rivers spread over the landscape periodically, allowing materials eroded from upstream to be deposited, thus enriching the riparian (riverside) soils. Additionally, natural grasslands often seem to build especially fertile soils. One of the most fundamental problems facing humans, especially when abundant and in cities, is that while natural ecosystems tend to maintain and even build soil over time, once the natural systems are cleared and replaced with agriculture, the soils tend to erode. The world is littered with the remnants of ancient cities that destroyed their soils, as Joseph Tainter develops in Chap. 4.

2.1.3 Water

Water is essential for life, and cities must have adequate water supplies if they are to survive and prosper. In general rain falls on mountainous areas and flows toward the sea. Humans capture and divert this water in many ways (see, e.g., [11, 12]). The major use is for agriculture but much water is diverted to meet the needs of cities. As cities have grown and local sources become increasingly polluted, they frequently have had to reach further and further to get the quantity and quality of the water needed. For example, New York City could get its water from the streams of Manhattan in 1800, but as the city grew, they reached north to the Croton watersheds and then the Catskill Mountains, several hundred kilometers away (and requiring transport under the Hudson River). Getting this water to New York was an amazing engineering feat! All other large cities, such as Manila in the Philippines, have had to reach further and further for basic resources as the city's population grew [13].

One can put all these ideas together and explain why the majority of the world's major cities are located on estuaries: these rare regions with access to cheap ocean transportation, in a depositional environment where soils are built and fresh water is constantly arriving from upstream (in rivers or pipes) and high intrinsic productivity of fish and shellfish because of the abundance of nutrients, are ideal locations for human settlement due to their high energy resources. Secondarily large cities are located along large rivers, for some of the same reasons.

2.1.4 Energy

Energy is required for all activity in all systems including the creation and maintenance of the structure that defines that system [14, 15]. All ecosystems, including natural and human built and their various combinations, require energy to build and maintain structure. Traditionally this energy is provided by sunshine and derivatives of sunshine including rain, wind, river flows, soil formation, timber, and food. But now that flow is tremendously supplemented by fossil fuels, much of which is used to concentrate water and food and other materials against gradients and to undertake maintenance metabolism to maintain structures. When there is a surplus above the level needed for maintaining the structure that exists, cities can grow. This fossil fuel supplement has allowed cities to become much larger, more complex and, often wealthy. Although some civilizations have existed in the Nile, Indus, and Huang Ho river valleys for many thousands of years, modern scholarship has shown that often cities and indeed entire civilizations go through cycles of growth and collapse (see Chap. 4). The principal reason many ancient civilizations have gone bust is that they depleted the resources upon which they were built by a combination of human population growth and resultant overexploitation of energy and other resources during initial good times. What is not known now is whether it will be possible to continue today's cities under a greatly restricted future fossil fuel budget, a very likely future scenario. This is likely to be the greatest challenge to city managers and other politicians in coming decades. Today we are ignorant or in denial of these issues, or blame other agents for the constrictions imposed by the increasing depletion of high-quality resources, and are completely unprepared for their inevitable consequences. The first steps to preparing for tomorrow are to identify and qualify what these energy flows are today (or were historically), and this chapter provides a blueprint for that.

2.1.5 Cities in Nature: The Role of the Sun

As stated above cities are subject to, and dependent upon, a myriad of solar energy-derived inputs: the various contributions to climate (including temperature, rain, river flows) and also food, animal motion, and all activities where there is motion. In fact, when anything moves, energy is expended. The source of virtually all this natural energy is the sun. A few exceptions are tidal motions in coastal cities and volcanic eruptions and related geological activity. The sun also is the source of a whole special group of actions or activities associated with life that we usually call photosynthesis (energy capture) and respiration (energy use), or somewhat more generally *production* and *consumption*.

2.2 Cities in Nature: Understanding Spatial Patterns of Production and Consumption

Although many think of human cities as “unnatural,” cities (in the sense of dense communities of animals in one place) also occur in many forms in nature. As such we can consider cities as regions where consumption is greater than photosynthesis. Perhaps the classic example in nature is an oyster reef. Here many thousands of individual oysters pile one on top of each other, in the process forming a many-roomed warren or, indeed, city, which is inhabited by various crabs, shrimp, bacteria, and other smaller creatures as well as the oysters themselves (Fig. 2.3). Each of these organisms requires its own energy source (i.e., food). In ecology we tend to use the word “trophic” (to refer to food), and the very abundance and density of animals in an oyster city make it necessary to supply a lot of food and carry away a lot of wastes. Where does the energy to support the oyster city come from? Well, like nearly any other organism, the food for oysters must come directly or indirectly from green plants. Oysters are filter feeders—that is, they get their food by filtering the phytoplankton (small plants that live suspended in the water) and other organic matters out of the water. They are so efficient that, supposedly, you can put a half liter of milk into 10 L of salt water with an oyster in it and return in an hour. The cloudy water will be clear as the very efficient oysters can filter out the milk particles. This efficiency of oysters causes a problem—they tend to deplete their food supply by their own filtering. But oyster reefs are always found where there are large tidal currents, what we might call *natural energy subsidies* to the oyster cities. By being concentrated in self-made cities, oysters increase the velocity of tidal waters over and through their cities, and this makes it possible to supply the needed food to, and carry away the wastes from, their cities and hence have the very large concentrations of animal life that they do have. Karl Mobius studied these things 150 years ago and writes of the complex animal community (which he called biocoenoses) that he found there [16]. Hence, we can say the trophic energy supplied to the oysters and the other residents of the oyster city is from both the solar energy captured by phytoplankton and the tidal energy subsidy that moves the trophic energy to the oyster city. Other natural cities include anthills, beehives, tree trunks vs. leaves, prairie dog cities, and so on (Fig. 2.4).

Thus, we can think of oyster reefs and other concentrations of animals in nature as cities, in the sense they have very high populations of at least one species and are centers of *consumption* of organic matter, which must be supplied by larger areas of *production* of organic matter somewhere else. In the case of oyster cities, the larger areas of production tend to be large bays where there is considerable energy capture from the sun by phytoplankton but without high concentrations of animals to use it. Tidal energies move the food to the oyster cities and remove the concentrated wastes of the oyster city. Speaking chemically, green plants reduce carbon dioxide (and other elements including nitrogen and sulfur) to generate energy-rich compounds that we call fuels, and animals, bacteria, fungi, and most other creatures use those fuels by oxidizing them to run their own metabolism. This is essential, for all organ-

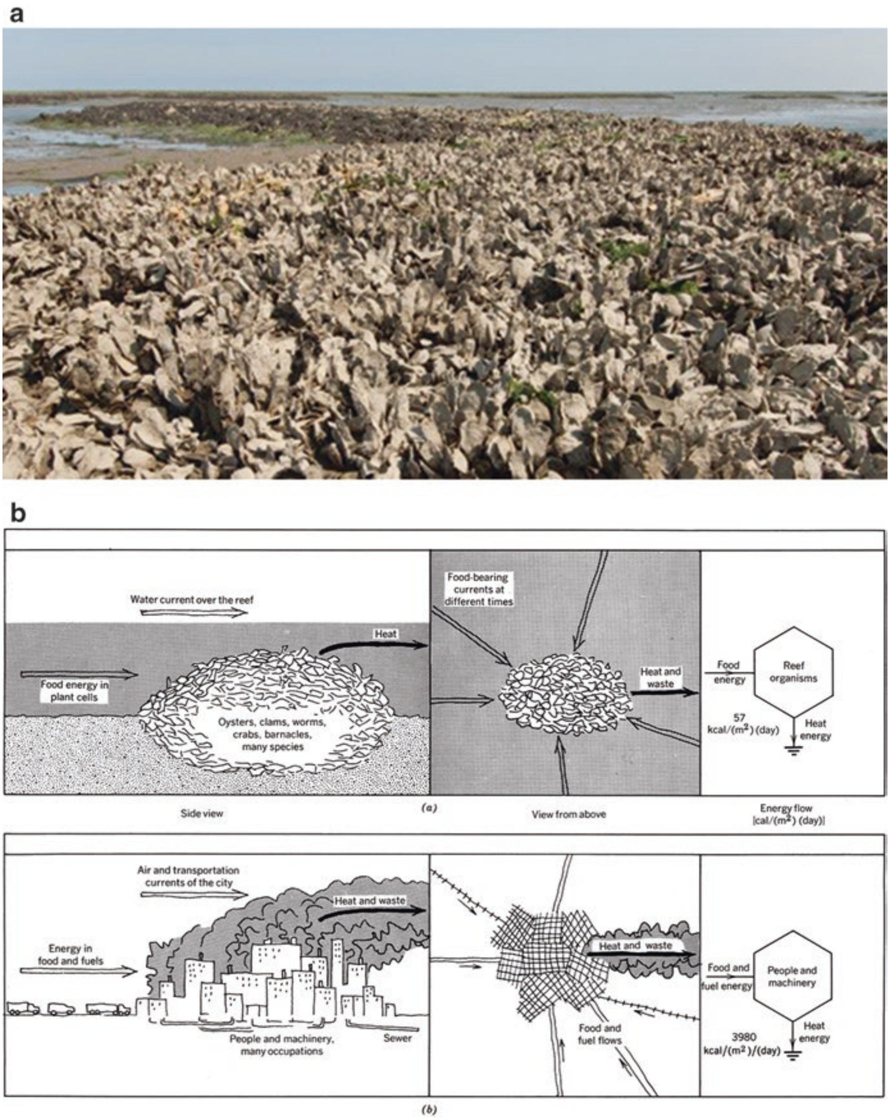

Fig 2.3 (**a**) An oyster city at low tide with a partial view of the bay area required to generate the plant material needed to feed it (Image source: Imarcade, public domain). (**b**) Comparison of an oyster city and a human city in terms of needs for inputs of food and other energy, dispersal of wastes, and transport systems. (From Odum [10], with permission of Wiley)

isms must have a constant supply of energy to “fight entropy,” that is, to invest in maintaining their own cellular and organismal integrity. We call this energy use *maintenance metabolism* and it is an absolutely essential activity. There is a continual recycling of matter between producers and consumers, between green plants

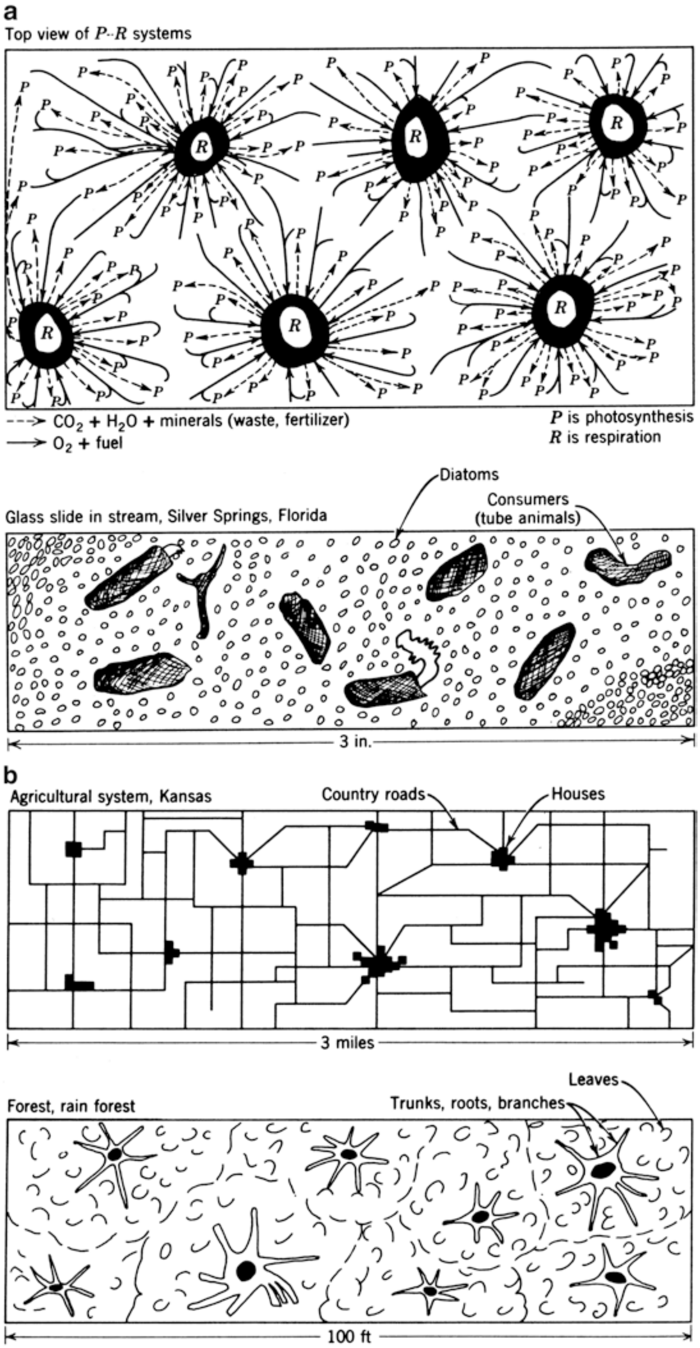

Fig. 2.4 Other "cities," or areas of concentrated respiration, in nature. (**a**) Plants illustrating the chemical reactions of photosynthesis where "fuel" equals carbon (C) and diatoms of algae in a stream; (**b**) Kansas agricultural system (e.g., corn or wheat fields) and a rain forest. (From Odum [10], with permission of Wiley)

and animals, for example, where the same carbon atom that existed in the atmosphere as CO_2 is reduced to sugars and other foods by plants and then respired by animals. Plants too must undertake maintenance metabolism, so the energy that is fixed by green plants must feed the plant's own maintenance requirements plus that of all other consumers. Usually the plants use roughly ten times more of their photosynthetic energy for their own needs compared to the smaller quantity that gets utilized by animals.

Humans, like oysters and ants, tend to be social animals. Humans do not live alone but rather in groups of various sizes, in part because their efficacy as hunters and gatherers—and later as cultivators and herders—tended to be greater when humans combined into small foraging units. Thus, human settlements tend to be characteristic of human populations even in the far-off past. These settlements, be they encampments of hunter-gatherers or today's megacities, collectively are centers of energy consumption that must be fed by photosynthesis and food chains from much larger areas (Fig. 2.5a). One of the most amazing things I ever experienced was to be on the highways at the wrong time (truck rush hour) north of Mexico City and thus to be caught in a caravan of tens of thousands of huge "semi" trucks that must bring every day the food, fuel, and other resources into a city of 20 million people. This also happens on a much smaller scale in Syracuse, although most of the collection centers are north of the city along the rail lines and not visible to students. Cities also have some natural energy flows, depending upon how "green" the city is, i.e., how much urban forest or parkland. But in no way can today's cities exist without enormous flows of fossil fuels bringing in their requirements for consumption from both nearby and distant areas of production.

Hence cities today can be examined using ecological concepts that were originally developed to follow energy through the food chains of natural ecosystems. This has been done recently for the city of Syracuse, New York, with an emphasis on the flow of food energy [17, 18]. The results, similar to the results of "ecological footprint" analysis, show that cities typically need areas tens to hundreds of times larger than their own area to provide the resources they require [19, 20].

2.2.1 Some Energy Terms from Ecology

Trophic dynamics is that part of ecology devoted to the study of the flow of energy through ecosystems. Solar energy is captured by *primary producers* (green plants) that are eaten by *herbivores* or *primary consumers* who are eaten by *carnivores* (or more specifically *secondary consumers*) and so on to the *top carnivore*. Decomposer organisms such as microbes break down organic matter back into inorganic forms. The specific function of a species in an ecosystem is called its *niche*, not to be confused with habitat (where it lives). A large tuna fish in the ocean, the top carnivore except for humans, survives and grows by eating energy that has passed through as many as five to seven trophic levels. Most of the energy that is captured by each trophic level is used for its own maintenance metabolism and movements so that

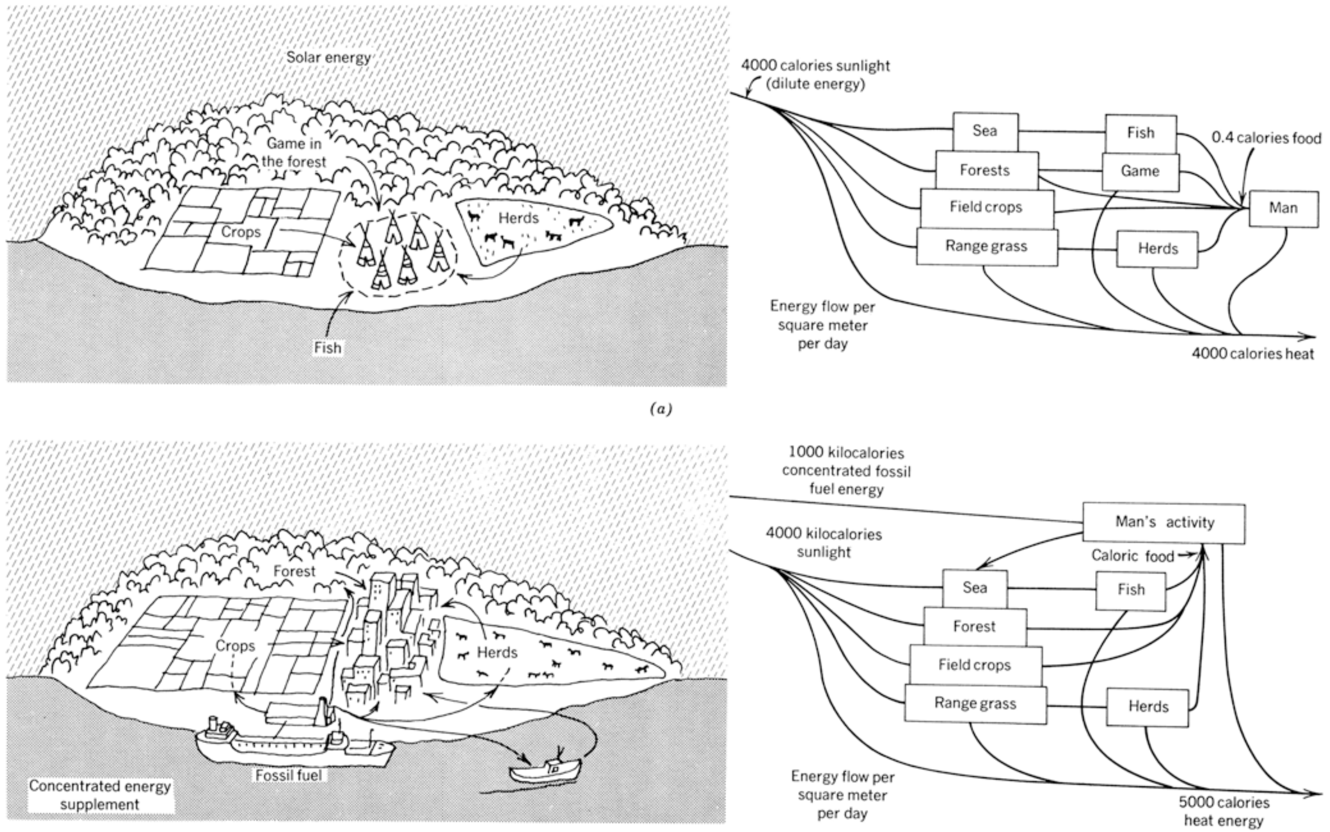

Fig. 2.5 Comparison of structure and energy flows of earlier Native American village (**a**) and modern city (**b**) on same site (From Odum [10], with permission of Wiley)

speaking generally only about ten percent of the energy captured by a given trophic level is passed on. Thus, it may take a million kg or more of phytoplankton to make a single tuna fish sandwich. Likewise, it takes a great deal of grass to grow a hamburger or a glass of milk.

Sometimes we use a shorthand to talk about these cycles: production = $\boldsymbol{P}$ and respiration = $\boldsymbol{R}$. Over a year for most ecosystems of a large enough size, and certainly the world as whole, P must equal R (i.e., the P/R ratio is one); in other words we cannot use more energy than is produced by plants. Similarly, for a city and its supporting agricultural region, $P = R$ over the year, although the P is diffuse and takes place over a large area, and the R is found both in the agricultural area and also concentrated in cities. Modern cities need much more than food, and one can think of food sheds or power sheds that must exist to support urban areas.

Synthesizing what we have said so far, cities are large areas in nature or dominated by humans where there is a great deal of trophic consumption and far less trophic production. Consequently, human cities, like oyster reefs, require energy subsidies. In antiquity this energy surplus came from surrounding agricultural fields, the labor of horses and slaves, and wind to blow sailing ships. More recently this energy subsidy comes principally from the use of fossil fuels (Fig. 2.5b). The larger external areas that support cities supply more than food. Concentrated ore bodies formed over millions of years are also necessary to support both preindustrial and industrial cities. Because the energy from fossil fuels is so much more concentrated than natural energy flows, this has allowed cities to become much larger over the past 200 years. Thus, human cities are probably no less natural than oyster reefs and are as common as oyster reefs once were. Some have argued that there is an "ecological determinism" about cities that they will inevitably come to exist because the concentration of consumption in areas of large energy use is the natural state of things, especially where there is an energy surplus [21].

2.3 Energy and Cities: A Historical Overview

Nearly all fuels used by humans in the past (wood, grain, grass, and other plants to fuel humans and horses) and even now (oil, gas, and coal) are *hydrocarbons* of one kind or another, and they have increased the comfort, longevity, and affluence of humans enormously, as well as, or perhaps especially, their population numbers. Most of these energy technologies rely on chemical bonds of hydrogen and carbon. Nature has favored the storage of solar energy in the hydrocarbon bonds of plants and animals because these elements are abundant and relatively cheap to obtain and because carbon has four valence electrons, capable of forming four bonds with other atoms and hence the very complex structures of biology. Bonds with hydrogen greatly increase the capacity to store energy in a molecule, and human cultural evolution has exploited this hydrocarbon energy profitably. Thus, plants and animals are carbon and hydrogen based (and some oxygen which is reflected in the "ates")—hence *carbohydrates*. All these developments assisted humans in their exploitation of colder, more northerly ecosystems. The most important of these new energy-based technologies was agriculture, which redirected an area's photosynthetic energy from natural to human food chains.

2.3.1 Human Cultural Evolution as a History of Increasing Control Over Energy

The history of human culture can be viewed as the progressive development of new energy sources and their associated conversion technologies [3, 22]. Even Stone Age technologies such as spear points and knife blades are energy related, specifically force concentration devices that allow humans to concentrate the force of their muscles onto an edge or point and hence undertake new kinds of work. These new work activities include penetrating the skin of a large beast or cutting animal skins into clothes. These activities in turn allowed the exploitation of more animal resources and colder climates. Fire was especially important as it allowed humans to cook plants and, in so doing, break down the cell walls of plant cells and hence get far more energy out of the food humans ate [23]. Fire also allowed humans to smelt metals and to bake ceramics. Wood was especially important as an early fuel, and entire subcontinents such as Peloponnese and India were deforested to get fuel [24]. Where regions were of relatively low productivity, especially of types that humans could utilize, people tended to become nomadic, in effect exploiting the productivity of a large area of relatively low productivity. Thus, hunters and gatherers had to travel over large areas to get sufficient food. Even so, studies of relatively modern hunter-gatherers, such as of the !Kung of the Kalahari desert in Africa, have found that their energy return on the energy they invested in hunting and gathering (*EROI*) is quite positive, about 10:1, and that they use this energy surplus principally in leisure activities such as storytelling and playing with their children [25, 26]. The necessarily nomadic lifestyle of many Native Americans in the American West was not understood by early European immigrants who coveted their lands and forced the original inhabitants on to reservations quite incompatible with their culture [27, 28].

Throughout human history, intermittent solar energy powered the development of society (which meant a subsistence lifestyle for most). Agrarian societies tend to have a very low societal EROI, 5:1 or less, compared to the EROI of the modern era, which has been as high as 30:1 [29]. The implication of such a low return on investment in agrarian societies is that there was very little discretionary income. In pre-industrial societies, most GDP was used to obtain basic energy to supply food, fodder, and wood fuel. For example, prior to the mid-seventeenth century, the English society spent between 50% and 80% or more of total expenditures to obtain basic energy to survive (food for humans, fodder for draft animals, and wood fuel), and climate patterns that influenced the size of harvests led to sharp swings in net energy and quality of life. Colonial empires resulted in the importation of enormous amounts of potential energy from colonies (in the form of food, wood, metals, ideas, slaves, etc.) that lowered the amount of UK GDP that was used to obtain basic energy. The industrial revolution increased efficiency greatly through the widespread exploitation of fossil fuels, automation, and use of electricity. This resulted in energy expenditure in the United Kingdom reaching a minimum of about 7% of GDP in the late twentieth century [30, 31].

2.3.2 The Dawn of Agriculture and the Evolution of Cities: Increasing the Displacement of Natural Flows of Energy

Beginning about 10,000 years ago, a remarkable change happened independently at a number of locations around the globe in human social organization. Humans begin settling down and began farming. Squash was cultivated in Mesoamerica, rice in China, and wheat, lentils, and flax in the "Fertile Crescent" in the vicinity of the Tigris and Euphrates valleys of present-day Iraq [2] (see Fig. 1.1). Up until that point, humans were constrained by their limited ability to exploit entirely natural food chains, due to the low abundance and poor digestibility of edible plants in natural systems. This was the hunter-gatherer lifestyle that had existed for millions of years since before *Homo sapiens* became a recognized species. The early farmers found out that they could increase the flow of food energy to themselves and their

Fig. 2.6 Aerial photograph of the remnants of the city of Ur (from which we get the word *urban*) and its ziggurat (massive building thought to be part of a temple complex), located in Mesopotamia (see Fig. 1.1). (Image source: Georg Gerster, via Science Source, New York)

families enormously by investing some of the seeds that might otherwise be eaten right away into more food for the future. How this happened is lost to antiquity, but as described by Jared Diamond in *Guns, Germs, and Steel* [21], it probably happened as people observed that their own kitchen middens (garbage areas) produced new crop plants from the seeds that had been deliberately or inadvertently discarded.

Agriculture spread rapidly around Eurasia and northeast Africa and it evolved independently elsewhere [2, 32]. Along with the development of agriculture, villages developed based on the net profits from farmers. However, these settlements were relatively small and did not have the characteristic attributes of full-fledged cities (extreme social stratification, monumental architecture, and large public works projects). The establishment of true cities characteristic of state-level organization did not occur until more than 5000 years after agriculture became established. But why did the establishment of cities take so long? Day and others [2] concluded that it was the stabilization of sea level after the last glaciation that provided the context and resources that allowed the initial state-level formation to take place. This has also been called pristine state formation. With sea-level stabilization about 6000 years ago, there was an enormous increase in coastal margin productivity due both to a large expansion in the area of highly productive shallow water habitat as the sea flooded over shallow continental shelves and a dramatic increase in productivity on an aerial basis. Day and others estimated that ecosystem productivity increased by about an order of magnitude. This provided high-quality food resources that subsidized the establishment of state-level organizations. This happened within a thousand years of sea-level stabilization, and within 1500 years, all initial state formations became established and almost all of them were in the coastal margin.

The first place this occurred appears to be in the Tigris-Euphrates river valleys where one of the first cities established was known as Ur (Fig. 2.6), from which we derive the word urban. Today we call that ancient civilization Sumer and the people Sumerians. There were many great cities of that time (roughly 4700 years ago) and regions, including Girsu, Lagash, Larsa, Mari, Terqa, Ur, and Uruk. Not only were many of these located on coastal margins (see Fig. 1.1) but these cities grew up in a heavily forested region, as can be understood from the massive timbers in remaining ruins, although today there are essentially no trees and no cities in that region. In fact, the forests were gone by 2400 BC. As a consequence, the harbors and irrigation systems silted in or required enormous energy to maintain, the soil became depleted and salinized, barley yield dropped from about 2.5 tons per hectare to less than one, and by 2000 B.C. the Sumerian civilization was no longer extant. The world's first great urban civilization, in fact its first great civilization, used up and destroyed its resource base and just disappeared over a span of 1300 years. These stories are well understood and told in fascinating detail in many places including by Perlin [24], Michener [33], and Tainter [34]. Other civilizations became established independently in the Indus River Valley in what is now Pakistan, the Yellow River Valley in China, on the western coast of South American in Peru, in Mesoamerica associated with the Grijalva-Usumacinta River delta, in the Mississippi at Poverty Point, and perhaps in the inner delta of the Niger River.

An important and not very pleasant take-home message is that most civilizations are temporary and thrive only while the economic resources that were the reason for their inception remain, even while most economic activities of humans in fact tend to erode, deplete, and poison the basic resources that supported the city in the first place. Today fossil fuels often restore needed resources, often from far away. But as fossil fuels become depleted, cities supported by the industrial revolution will likely fade, at least if there is not a huge development of nuclear or solar-based energy.

The implications of agriculture for humans were enormous. The first, seemingly counterintuitive, is that human nutrition, size and health, on the average, declined. One of the best studies to document this was performed by Angel, who studied the bones of people buried over the past 10,000 or so years in Anatolia, roughly the area that currently encompasses the border region of modern day Turkey and Greece [6]. Angel was able to date the bones that he found in ancient burial grounds and could tell many things about the people who once lived there from the bones themselves. For example, their height and general physical condition, as well as functions of the quality of nutrition, could be determined by the length and strength of the bones. Bones could also show the number of children a woman had by the scars on the pubis or whether that person had malaria by the appearance of the bone marrow-producing regions of the bone, and so on. The data indicate that the people actually became shorter and smaller with the advent of agriculture, indicating a *decrease* in nutritional quality. In fact, the people of that region did not regain the stature of their hunter-gatherer ancestors until about the 1950s. Thus, although agriculture may have given the first agronomists an advantage in terms of their own energy budgets, that surplus energy was translated relatively quickly into more people with only an adequate level of nutrition as human populations expanded. Similar findings were reported for the Maya where populations that had access to coastal resources were healthier than inland populations. Nevertheless, there was an enormous increase in the food available per area which allowed for great population increases. Increasingly some of this increase in population was concentrated in cities, which grew as the demand for their trade, artisans, and special products increased. One of the clear consequences of agriculture was that people could settle in one place, so that the previous normal pattern of human nomadism, where people had followed seasonal patterns of game and plant fruition, was no longer the norm. As humans occupied the same place for longer periods of time, it began to make sense to invest their own energy into relatively permanent dwellings, often made of stone and wood. There began to be sufficiently durable human structures to leave significant artifacts for today's archeologists.

The second implication was, as outlined below, that fewer people needed to be involved in the securing of food. Many people were freed up to become artisans, priests, and political and military leaders, not to mention soldiers, especially in the fallow seasons. From an ecological perspective, we can say that there was the development of many more niches, or functions or roles, that people can fill and this was initially based on increases in coastal margin productivity. Cities also allowed concentrations of powers, which increased the ability of governments and despots to extract more of the surplus taxes (often in the form of grain) through coercion.

Where nomads and settled people (i.e., agriculturalists) met, there were often fierce conflicts based on perspectives of cultural (or religious) superiority. A very interesting assessment of the energy cost of trade and conflict in seventeenth-century Sweden is found in Sundberg [35]. In this case huge areas of productive forests were required to generate charcoal and hence the iron weapons of soldiers. A classic but historically much later example is where European American farmers met nomadic Native Americans in the 1700s and 1800s. Such conflicts are occurring today where nomadic Maasai herders in Kenya are finding that many of their ancestral grazing grounds are occupied by farmers with growing populations.

The third main consequence of agriculture, coupled with the dramatic increase in coastal margin productivity, was an enormous increase in social stratification—a precursor of state-level formation. The increase in resources available to Neolithic village dwellers allowed economic specialization to become more important. For example, if one individual was particularly skilled at generating agricultural implements or understood the logic and mathematics (i.e., to derive the best planting dates) of successful farming, it made sense for the farmers of the village to each trade with him some of their grain for implements or knowledge, initiating, or at least formalizing, the existence of markets. From an energy perspective, relatively low-priced (because so many people had the necessary skills) agricultural labor was being traded for the high-priced labor of the specialist. The work of the specialist, when it was good, can be considered of higher quality in terms of its ability to generate greater agricultural yield per hour of labor. Considerable energy had to be invested in training that individual through schooling and apprenticeship. The apprentice had to be fed while he or she was relatively unproductive, anticipating greater returns in the future. Thus, we can say that the EROI of the artisan was higher than that of the farmer, even if less direct, and often his or her pay and status as well. But as noted above, state-level formation did not take place until about 5000 years after agriculture became established, and this was subsidized by the enormous increase in coastal margin productivity after sea-level stabilization.

A fourth consequence of agriculture was that the interaction of people with *cultivars* (plants that humans cultivate) also changed the plants themselves greatly. All plants are in constant danger of being consumed by herbivores, from bacteria to insects to large grazing or browsing mammals. In the past herbivorous dinosaurs filled the niche of today's mammals. The evolutionary response of plants to this grazing pressure was to derive various defenses, including sometimes physical protection (such as spines, especially abundant in desert plants) but more commonly chemical protection in the form of such chemicals as alkaloids, terpenes, and tannins. These compounds place a heavy burden on herbivores or potential herbivores by discouraging consumption or by extracting a high energy cost for those doing so, for the energy cost of detoxifying poisonous compounds is very high [36]. Humans do not like these frequently bitter, poisonous compounds either and for thousands of years have been preferentially saving and planting the seeds from plants that taste better or have other characteristics that humans like [37]. Partial exceptions are, e.g., mustards, coffee, tea, cannabis, and other plants whose bitter alkaloids are poisonous if that was all we ate but an interesting dietary supplement for some in small doses. Consequently, our cultivars are, in general, quite poorly defended against insects and have required us to invent and use external pesticides, with complex consequences. Many of our cultivars would not survive in the wild now and have coevolved with humans into systems of mutual dependency. A visitor from outer space might conclude that the humans have been captured by the corn plants who use us for their slaves to make their lives as comfortable and productive as possible! Meanwhile all kinds of pests were themselves adapting to the concentration of humans and their growing and stored food, often with disastrous impacts on humanity [38, 39].

There were many other implications of the coevolution of agriculture, agricultural surplus and cities. Granaries were required to store food, and this gave increasing power to those who controlled the granaries. Agricultural surplus meant that humans could focus on other things besides getting food, the principal occupation of hunter-gatherers. This allowed the development of tool makers, artisans, providers of luxury goods, soldiers, and even professional intellectuals.

Cities spread about the world, so that by 5000 B.C. very large cities began to be established and within 1500 years existed in Egypt, the Indus and Yellow river valleys, Mexico, and Peru. These cities, certainly those on different continents, apparently evolved quite independently, implying that there is some kind of "natural selection" for cities once a sufficient energy surplus is met. The main arguments put forth are that cities are especially important for commerce, for specialization of human function, and for various aspects of social quality of life. But cities have serious ecological liabilities too. They require a constant input of food and fuel and a constant removal of wastes. If these are not well taken care of, then an outstanding feature of cities is their ability to enhance the transfer of disease germs due to the overwhelming of the natural process of waste recycling and close human contact, insuring easy transfer of pathogens (disease organisms). While we normally think of history as being about leaders and battles, a lot of what happens depends upon "rats, lice, and history," that is, on disease carriers such as rats and lice and the diseases they carry that also infect humans.

2.3.3 The Trophic Situation of Cities Today

The primary (plant) production of natural ecosystems varies from about 2000 (desert or tundra) to 25,000 (deciduous forest) to 35,000 (estuary or tropical rain forest) kilojoules per square meter per day, depending on latitude and moisture. By contrast the fossil fuels used in cities is typically vastly greater, from millions to billions of kilojoules per square meter per year [40]. Average energy consumption today in subsistence-level countries is about 500 W, or about five times basic metabolic requirements, while in highly urbanized first-world countries, per capita energy consumption ranges from 10,000 to as high as 50,000 W [7]. Plant production remains at levels perhaps similar to the original ecosystems in a few parks, and less in vacant lots and lawns, and obviously near zero in paved or constructed areas. While the P/R ratio is often similar in many natural ecosystems, the P/R ratio of cities is very, very small. Hall [41] found respiration exceeded production in three urban neighborhoods by some 200–700 times. This reflects the concentrated respiration of residential household and vehicle fuels brought in from outside the city. If food consumption were included P/R ratio would be even smaller.

Another important issue relative to the trophic analysis of cities today around the globe is the increasing affluence of many areas, which brings with it an increasing consumption of protein, meaning that an extra step in the trophic chain leading to humans and a much greater need for plant material since the transfer of plant to animal energy is only 10 or 20% efficient. Wolman [42] has examined the metabolism of cities in a very general way including the needs for import and export of water and other materials. Bai [43], for example, argues for a systems approach (meaning a comprehensive and systematic examination of the important issues and the resources needed and interactions of each) for understanding the ecology of cities if we are to adjust to the many issues facing cities as we increasingly concentrate people and their needs and wastes into smaller areas. Good examples are Zucchetto [44] for Miami and Huang and Hsu [40] for Taipei. Very comprehensive tools for a systems approach are available in Odum [45].

2.3.4 Selective Processes for Cities

Once there was sufficient net energy surplus from farming to allow people to live off the farm (or their immediate vicinity), initial cities arose based on increases in ecosystem productivity and became centers of trade, points of defense, and as centers of administration, taxation, and entertainment. The most famous example from antiquity was the silk route (or routes), followed by Marco Polo, where (among many other things) fine fabrics and spices from the East were brought by horse and camel thousands of miles to Europe, where they were sold at very high prices. A series of cities developed along the silk route, including such familiar ones today as Venice, Constantinople, Damascus, Palmyra, Baghdad, Tehran, Kabul and various cities in China including Nanjing. Trade also flourished in seaside cities where initial cities were established. For example, the Lebanese were known as seafaring traders about the Mediterranean for many thousands of years B.C.E. The Maya had extensive marine trade along the shores of the Yucatan Peninsula. Lisbon at the mouth of the Tagus River was a center of long-distance trade, especially once the Portuguese learned how to sail easily around Africa to enter the very profitable spice trade, and the Vikings, often sailing from Oslo, were probably more traders than raiders. Thus, the principal incentive for concentrating people in cities has probably always been economic, resulting from the benefits accruing from the concentration of resources and skills for specialized innovation, manufacture, and exchange.

A second strong incentive for the evolution of cities was the need for defense. Humans have been raiding, quarreling, and warring since our ability to have any record of their activities. Hunter-gatherers certainly quarreled, but their nomadic existence probably made them difficult targets for deliberate military campaigns whereas cities were readily located. Plutarch (e.g., [46]) gives many biographies of ancient people whom he and others celebrated for successfully attacking other cities and bringing back loot to their own. Early cities often had extensive walls for defense, obviously constructed at great expense. Ancient Athens, for example, was completely surrounded by walls which kept the Spartans out for most of the Peloponnesian wars (e.g., Thucydides translated by [47]). Italy is covered with walled cities reflecting the past time of persistent insecurity. Of course, cities also served as centers for the garrisoning and training of predatory troops. These defensive works were often made of trees and contributed to the complete deforestation of much of the ancient world again and again. Likewise many ancient forests were obliterated to get fuel to smelt silver to pay for the armies [24, 48].

A third incentive for the evolution of cities is that as more differentiated skills evolved, they served as a focal point for finding them, so that, e.g., farmers needing a new type of plow or seed would know where to go to get the service they needed. Some of these new inventions were for entertainment and education (music, plays, books, and so on). Thus farmers, the majority of people until recently, would often come to towns or cities on the weekend to sell their produce, get more specialized products, and enjoy some entertainment. All of these factors generated financial incentives for the growth of urban areas. There were probably many other more specific reasons, but these three appear to be general. In all cases, state-level formation led to the concentration of wealth at the top and extreme economic inequality.

2.3.5 The Development of Factories and the Industrial Revolution

The prime enabler for the initial development of cities was the development of agriculture followed by the expansion of coastal margin productivity and the surplus energy they generated. The expansion of colonial empires beginning in the first millennium B.C.E. right through the age of European colonialism provided stores of potential energy imported from colonies in the form of food, timber, precious metals, ideas, slaves, etc. The initiation of the industrial revolution accelerated the development of urban areas and came with expansion of mass production and factories, especially as enhanced by fossil energy, starting in the mid-eighteenth century with coal and continuing through today based on coal, gas, and oil plus smaller quantities of hydropower, nuclear, and most recently wind and photovoltaic energy (e.g., [49]). The global use of hydrocarbons for fuel has increased nearly 800-fold since 1750 and about 12-fold in the twentieth century alone, roughly two to five times the rate of human population increase (Fig. 2.7). This allowed each human to do enormously more work, in agriculture, factories, war, and many other aspects of human existence.

Thus, as history progressed, so did the energy resources used by humans: from one's own muscles to slaves to draft animals to coal, oil, and gas, collectively called fossil fuels. Throughout most of human existence, wood served as the main energy resource for cooking, warmth, and smelting metals, but wood was displaced by fos-

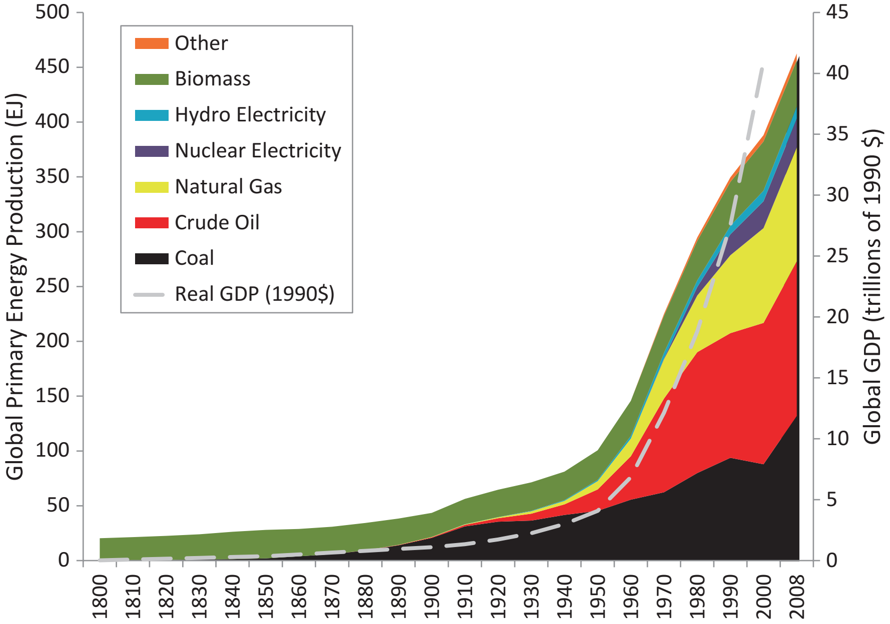

Fig. 2.7 Pattern of increased fossil energy use for the world over time and also the similar increase in the world economy

sil fuels in the nineteenth century (Fig. 2.7). By the late eighteenth century, new sources of energy were being developed in, for example, New England, where the abundant water power potential allowed enormous, by the standards of the time, new factories to be built making textiles, shoes, chemicals, and all manner of iron tools and equipment. This allowed the development of great concentrations of workers in such towns as Manchester, New Hampshire, Lowell, Massachusetts, Boston, New York City as well as the cities to the south along the fall line, as previously mentioned. Water-powered machines greatly increased the quantity of goods a laborer could generate in an hour (i.e., labor productivity) and the subsequent wealth of at least some in New England. All of these activities, and the energy behind them, are considered the beginning of *industrialization*, the increasing use of water, wind, or especially fossil energy to increase the manufacturing of goods in factories, places of concentration of people and machines. Meanwhile as forests were cleared for agricultural land and for homesteads in New England, Europeans spread to the Southeast and then westward to virtually the entire Midwest, where enormous amounts of wood fuel were available for all manner of local industries. Fish too were abundant, and the world's vast number of whales was greatly decreased by Massachusetts seafarers in order to get whale oil, the principal source of lighting in the middle of the eighteenth century. It is clear that if fossil fuels had not existed, the industrial revolution would have been limited by resource scarcity of whale oil, forests, water, and wind power.

At the start of the nineteenth century, England and Germany had begun their great industrial transformation, using the concentrated solar energy found in coal to generate enormous new amounts of high temperature heat that allowed far more work to be done than was the case with water power, wood, or charcoal. Of particular importance was the development of the James Watt steam engine and its application to many activities, especially transportation with railroads. This technology was transferred to the United States, which had very rich coal reserves. By 1850, the United States had built 9000 miles of railroads and by 1890 about 160,000 miles. These railroads quickly replaced other means of transport between cities, such as the Erie Canal in New York, and made moving people and freight between cities enormously easier and cheaper and more rapid. In 1859, Colonel Edwin Drake drilled the world's "first" oil well (although oil wells were drilled 4 years earlier in Petrolia and Oil Springs Ontario), and kerosene began to replace whale oil as the lighting source of choice (fortunately, as many whale species were being hunted to near extinction). Perhaps the most concentrated early industrialization occurred in and near the city of Buffalo as the water flowing over Niagara Falls was increasingly exploited to generate electricity. The enormous wealth generated by the new industrialization allowed the "captains of industry" to become enormously rich by world standards. This, along with the great disparity in wealth between them and their workers, generated the phrase "The Gilded Age" for the 1890s. But it was not a smooth pattern of growth, as periodic depressions caused a serious loss of wealth for many people, rich and poor. Most people continued to be poor, or at least far from affluent, making barely enough to survive and have a family. In America, despite the disparities in income, the wealth distribution was quite equitable compared to Europe and most of the rest of the world, in part due to the ability of many to have access to land and its solar energy (once the Native Americans were displaced) through farming or with axes. Large dams, built with the help of massive oil and coal-powered machines, brought irrigation water and electricity to many in rural areas, resulting in huge additions to the availability of biological and physical energy for each American. Nevertheless, most of this industrial activity was concentrated in cities, and cities become more and more important economically as well as a place for people to live.

In 1900, the United States ran principally on coal, wood, and animal power. Then in 1901 came the huge Spindletop oil well and many wells like it. As the twentieth century evolved, the United States, dominated by European Americans, was becoming the world's emerging agricultural and industrial giant. Oil became increasingly important with the new oil wells and the development of automobiles, trucks, and tractors that could run on what had formerly been a waste product of the kerosene industry—gasoline. For the first time a very large proportion of the population of an entire country was becoming fairly affluent, and some were becoming extraordinarily so. This enormous affluence was associated with, and clearly dependent upon, an increasing use of energy that expanded at almost exactly the same rate as the increase in wealth as measured by Gross Domestic Product (GDP) (Fig. 2.7). Most generally, hydrocarbons have generated an enormous increase in the ability of humans to do all kinds of economic work, greatly enhancing what they might be able to do by their own muscles or with those of work animals with, eventually, fossil-fueled machines such as trucks and tractors as well as machines in factories (Fig. 2.8). This work includes, perhaps most importantly, the production of food for humans.

Some say that today we live in an information age, or a post-industrial age. This is not really true. Today we live in a petroleum age. Just look around. Transportation is dominated by oil, and all of our plastics and most of our chemicals are made from natural gas or oil, as are the fertilizers that feed our food sources, fuel the tractors, etc. Thus hydrocarbon-based energy has been important for the three main areas of human development: economic, social, and environmental. Overtime we have needed a smaller and smaller proportion of our total economic activity to get the energy needed by society (Fig. 2.9). Given that, we need to think a lot more about the quality and quantity of petroleum that will be available for our use.

2.3.6 Quality of Petroleum

Oil is a fantastic fuel, energy-dense, relatively easy to transport and use for many applications, and extractable with relatively low energy cost and (usually) environmental impact. What we call oil is actually a large family of diverse hydrocarbons whose physical and chemical qualities reflect the different origins and, especially, different degrees of natural processing of these hydrocarbons. Basically, oil is phytoplankton (small aquatic or marine plants) kept from oxidation and then pressure cooked for 100 million years or more. In general, humans have exploited the large reservoirs of shorter-chain “light” oil resources first, because larger reservoirs are easier to find and exploit and lighter oils are more valuable and require less energy to extract and refine. Therefore, over time in mature regions, the initial exploitation of the highest quality has often required the exploitation of increasingly small, deep, offshore, and heavy resources. Progressive depletion also means that oil in older fields that once came to the surface through natural drive mechanisms, such as gas pressure, must now be extracted using energy-intensive secondary and enhanced technologies. Thus, technological progress is in a race with the depletion of higher-quality resources. The net effect is a decline in the “energy return on investment” (EROI) of oil as a resource. The United States once obtained 30 or more units of energy for each unit spent in seeking it. More recently this has declined to 10 or fewer returned per unit invested [52], and a number of researchers have concluded that and EROI of a minimum of 10:1 is needed to fuel a modern industrial society. Another aspect of the quality of an oil resource is that oil reserves are normally defined by their degree of certainty and their ease of extraction, classed as “proven,” “probable,” “possible,” or “speculative.” In addition, there are unconventional resources such as heavy oil, deep-water oil, oil sands, and shale oils that are very energy intensive to exploit. This means that in the future there will be less net energy delivered to society from whatever energy is produced, and a greater proportion of all economic activity must be diverted to get the energy to run the rest of the economy.

Fig. 2.8 Example of the increased work that fossil fuels allow, in this case by comparison of (**a**) a 33 horsepower combine 100 years ago and (**b**) a 200 horsepower combine of today. (Image sources: (**a**) Photograph—“Evolution of Sickle and Flail—33 Horse Team Harvester, Cutting, Thrashing, and Sacking Wheat, Walla Walla, Washington,” copyright 1902 Underwood and Underwood, now public domain [50]. (**b**) New Holland Tractor Advertisement)

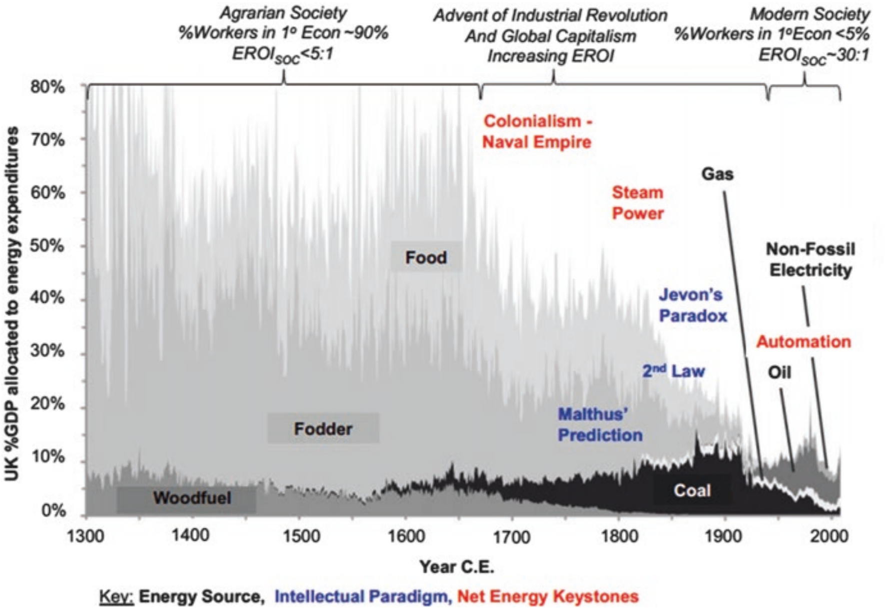

Fig. 2.9 Percent of GDP allocated to energy expenditure in the United Kingdom from 1300 to 2008. Energy sources are labeled in black, keystone innovations are labeled in red, and intellectual paradigms are in blue. Adapted from Fizaine and Court [51]

2.3.7 *Quantity of Petroleum*

Most estimates of the quantity of conventional oil resources remaining are based on "expert opinion," which is the carefully considered opinion of geologists and others familiar with a particular region. The ultimate recoverable resource (URR) is the total quantity of oil that will ever be produced, including the 1.3 trillion barrels extracted to date. Recent estimates of URR for the world have tended to fall into two camps. Lower estimates come from several high-profile analysts with long histories in the oil industry. They suggest that the URR is no greater than about 2.3 trillion barrels and may even be less (e.g., [53]). A higher estimate of 3 trillion barrels is the middle estimate, and 4 trillion is the highest estimate, from a more recent study by the US Geological Survey [54]. About half of the roughly 1.4 trillion barrels that the USGS predicts remain to be discovered are from new discoveries, and about half are from reserve growth. The latter describes the process by which technical improvements and correction of earlier conservative estimates increase the projected recovery from existing fields. This relatively new addition to the USGS methodology is based on experience in the United States and a few other well-documented regions. The new totals assume, essentially, that petroleum reserves everywhere in the world will be developed with the same level of technology, economic incentives, and efficacy as in the United States. Although time will tell the extent to which these assumptions are realized, the last 10 years of data have shown that the majority of countries are experiencing patterns of production that are far more consistent with the low EUR estimates as compared to the higher EUR estimates [55].

Recently a new technique, called "horizontal drilling and fracking," has allowed the exploitation of formally uneconomic oil deposits. This has resulted in the reversal of the long-term decline in US oil production, and in 2017 production rates exceeded the previous peak in 1970. However it is not known how long this approach will be effective, and as of this writing the industry is not making money from the process [56]. Additionally, there are increasing concerns about climate change resulting from the burning of fossil fuels. There are many who believe that the new "cleaner" technologies of photovoltaics and wind turbines will be able to replace fossil fuels. But as of this writing, these new technologies are only about 2% of total energy resources. If they are to displace fossil fuels, they have a long way to go. On the other hand, their price is coming down, and many are optimistic.

2.4 Biophysical Reality and the Future of Cities

Now more than half of humanity lives in cities, the so-called urban transition. Modern, first-world urban areas use enormously more and more energy per capita (in part because they tend to be on average wealthier – see below). Thus, it is critically important for them to have sufficient energy in the future. But there are other concerns as well. Probably top on the list is the potential for climate change. Probably most importantly it appears that cities are getting warmer not only from global changes, but because as they get larger, a larger proportion of them is paved over, which absorbs more sunlight [57]. One response around the world is more and more air conditioning, and air conditioners (which are heat exchangers) expel hot air into the atmosphere outside their buildings, contributing further to the heating of cities. One way to cool cities, covered in Chap. 7, is to increase the green (i.e., living plant) infrastructure, which tends to cool city air through shading and transpiration (evaporation through leaves). Another issue is increased flooding and droughts, again caused by both global trends and also by human action, such as paving over soils that used to soak up rain water (see Chap. 6). Hence floods are becoming more frequent in part because of ways that humans are changing the local as well as global environment.

Many cities proclaim themselves "green" or "sustainable" in various ways, but few have undertaken the energy and material analyses (such has been done by Huang and Hsu [40] and Zucchetto [44]) that might allow one to determine whether such self-promotion is factually correct. Day and Hall [8] suggest that "green" Portland is no more sustainable than is nearby Seattle, or indeed essentially any other city of its size. Modern industrial cities use enormous amounts of energy. Burger et al. [7] reported that per capita GDP, energy use, and greenhouse gas emissions go up by 2–3 orders of magnitude from the poorest developing countries to highly urbanized developed countries. Fix [58] concluded that the idea of decarbonization through services is not correct because of the high direct and indirect energy use by rich urban areas.

Even the concept of reducing fossil fuels to reduce carbon dioxide release has within it many problems, since solar alternatives such as photovoltaics and wind turbines are very energy expensive to build and are plagued with intermittency since cloudy, windless days are common in many parts of the world and storage of electricity is expensive in terms of money and energy. Certainly, resolving these issues, if that is possible, is one of the greatest challenges facing the future of [8, 49].

Today many cities are turning into megacities around the globe (see UN projections in Table 1.2). While there are many jobs and amenities that make these huge cities attractive to people, they are also often extremely crowded, polluted, and expensive. There are some who move out of the large cities to seek a simpler life. But is that possible for entire populations? Have we generated a situation where cities *must* continue to function, for we have no alternative as there is no going back to the simpler lives of our grandparents because there are now so many of us? If so how can we assure that our cities are sustainable in terms of food, water, energy, and the other necessities of life? Thus, human cultures must make decisions about investing our remaining fossil energy resources (both personally and collectively) into ways that contribute to the long-term survival of cities. We know from archeologists, such as Joseph Tainter, that history is littered with once-proud cities and indeed entire civilizations that were, in their way, as powerful as ours today but which exist now only as piles of rocks under desert sands or jungle vegetation. We were not aware of the extent, or even of the existence, of many of these once-huge civilizations until recent years when we have been able to peer at landscapes from satellites. This is not necessarily the fate of all civilizations, for example, more or less continuous civilizations have existed in the Nile, Indus, and Huang Ho river valleys for many thousands of years, but even these civilizations have waxed and waned and the majority of civilizations, as represented by their major cities, have simply disappeared. Likewise, there are often disappearances of large parts of societies. Why is this the case? There are many possible causes, of course. They include destruction from invading forces (e.g., ancient Rome at the hands of the Vandals and the Goths who were fierce horsemen from Central Asia), racism that threw out the most productive and clever components of a society (Jews and Muslims in Spain in 1492), diseases (many plague-ridden cities in Europe in the fifteenth century), and simple greed of the ruling class which has led to social upheaval (the French Revolution brought down the French royalty/aristocracy). In all cases, the reduction of energy sources contributed to the problems.

Modern scholarship has shown that the principal reason many ancient civilizations have gone bust is that they depleted the resources upon which they were built by a combination of overexploitation and human population growth during initial good times. The most common examples are water (see James Michener's *Caravans* [33]); soils, e.g., the Maya (see Tainter [34] and also Diamond's *Collapse* [59]); and, especially, forests and the soils they nurture and maintain. A wonderful book for any student to read, in fact a must, is John Perlin's *A Forest Journey* [24]. Perlin shows how the history we have been taught throughout our entire educational process simply ignores what is often the most critical element: the availability of or, through overexploitation, non-availability of large trees. Historically, large trees have been essential, not only for constructing houses, palaces, and ships but also as an energy supply that allowed the smelting of metals. Other books that make a similar case, although from somewhat different perspectives, are Ponting [60] and Redman [48]. The point of all these historical studies is that while we tend to assign the events of history to great men and women, no Phillip of Macedonia, Julius Caesar, Cleopatra, Catherine the Great, Admiral Nelson, nor Napoleon could have become successful without their respective natural resource bases. This is a perspective of history obvious to an ecologist but missing from most of our history lessons in school [7]. It is a perspective also missing from our conventional teaching of economics. A recent and realistic approach is found in biophysical economics [15].

2.5 Conclusions/Summary

Cities are concentrations of people and other animals at intersections of transportation corridors and/or where important resources are abundant. They can exist only by exploiting the resource base of a much larger region where additional resources are produced. Like oyster reefs they are islands of consumption within a sea of producers, and they require massive amounts of energy to concentrate the fruits of their sizable “ecological footprints” (i.e., the area of the rest of the world required to supply their needs and to dissipate their wastes) into relatively small, dense urban settings. Consequentially the metabolism of the area switches from the usual near balance of production to respiration to a much higher respiration (energy use) compared to production (energy production). As global populations have passed through the urban transition with more than 50% of the human population now living in cities, increasing amounts of fossil energy are required to produce and move the food and other materials required into the cities. This has led to a great increase in greenhouse gas emissions. Humanity will face new challenges as the oil and other fossil fuels upon which we have become so dependent become, inevitably, less available in the future. It is not clear whether the function of these fossil fuels can be replaced with other sources of energy. It is not unlikely that the age of the modern industrial city will soon begin to wane.

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Chapter 3
Social Processes, Urban Ecosystems, and Sustainability

Richard C. Smardon

Abstract The purpose of this chapter is to understand social science concepts and governance approaches useful for managing urban ecosystems sustainably. Basic social science concepts, urban ecosystems/social science terminology, theoretical models, and applied social science research will be reviewed with this perspective. Environmental services derived from green space and green infrastructure will be a strong subtheme in regard to its quality of life and human health benefits. Social science models and constructs with high potential for applicability to sustainability planning will be featured through several case studies.

Keywords Urban social science · Urban ecosystems · Social benefits · Decision-making

3.1 Urban Social Science Theory

Many planning practitioners and academic researchers have been studying the urbanization process of cities for many decades. This includes urban planners [1–5], geographers [6–10], sociologists [11–16], environmental psychologists [17–23], historians [8, 24–28], and others. This section will provide a brief overview of some of the most influential voices impacting urbanization social theory from a systems perspective.

In North America there was a tradition of urban studies called the Chicago School, which examined cities as systems. Two of the most influential early works were by Park and Burgess [10] and Haig [29] who developed the *historical theory* of urban form or the *concentric zone hypothesis* of how cities developed. This the-

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ory was that houses were built for the well-to-do toward the center of the city, which then over time trickled down to the lower-income residents as the richer residents moved out toward the suburbs and then back inward with urban renewal over time. Key components of such a historical theory included aging of structures, sequential occupancy by income levels, and population growth [24].

Also providing historical context is the work by geographer David Harvey who, in his book *Social Justice and the City* [6], writes about social processes and the spatial form of urban areas as well as the distribution of resources and equity issues. Also, William Cronin provides us a rich historical context for urban area development of the Chicago metropolitan area over time with his book *Nature's Metropolis* [25]. Peter Saunders addresses the multidimensionality of social theory and urbanism that includes capitalism, ecological context, cultural form, socio-spatial system, ideology, and spatial definition. Finally, we have Jane Jacobs in *The Death and Life of Great American Cities* [27] who critiques the physical determinism of urban planning and endorses watching how people behave in order to identify urban qualities and what urban spaces to save or enhance.

During the last 30 years, *contextualist* theories of society and urbanism have emerged to challenge the more traditional *reductionalist* approaches that present society as an aggregation of individuals with rational self-interest behavior [12, 13, 30]. Contemporary social theory presents “individuals as social beings whose actions reflect their socially-derived meanings, values and knowledge” (p. 138 in [13]). Such behavior is seen as a complex, reflexive process of engagement—contingent on many factors such as responses to emotional attachment feelings, trust in authority, and beliefs (or not) that individual actions will affect outcomes. Social and cultural status of institutions may be important factors in determining the public's trust in such information [31]).

Reductionist theory and models favor individual preferences as expressed through the market; allocate the power of decision-making to experts and professionals; and perpetuate existing rights and decision-making power, i.e., does not welcome new players at the table [2]. Contextualistic approaches, by contrast, favor stakeholder involvement by anyone interested in the outcome. Both theoretical approaches can be used for studying urban systems, but recent trends favor contextualistic approaches. Such social approaches bring an additional set of complexities, relationships, and additional flows of energy traditionally studied in ecology.

Current social science approaches to urban ecosystems include the *governance approach*, the *land use/landscape* approach, and the *ecological metabolism* approach. The *governance approach* draws from contextual social science and emphasizes the importance of a broad array of actors and institutions and also the temporal patterns in social-ecological systems. This approach is useful in addressing four major urban ecology issues:

- Understanding the condition and organization of nature in the past
- Exploring interactions between social conditions and the economy, environment, etc.
- Determining environmental policy and decision-making

- Probing the intellectual history of environmental consciousness as it relates to community attitudes [28]

The *land use/landscape approach* emphasizes the importance of spatial patterns in social-ecological systems. Considerable progress has been made linking social dynamics and spatial patterns, thus addressing scaling issues [32]. Scaling issues usually involve looking at an area from large scale to smaller scale as well as nested scales. Important linkages exist between metabolism and land use such as change in socioeconomic metabolism that have transformed landscapes [33]. An example is the increased urbanization decreasing green space, green infrastructure, and the ability to absorb environmental pollutants.

Social-ecological metabolism is the sum total of chemical processes that occur in a living organism, resulting in growth, production of energy, useful work, elimination of waste materials, transport, and production [34]. For social systems this includes reproduction of human populations as well as economic production and consumption processes requiring material and energy flows [35, 36] and is described in Box 3.1. *Metabolism* provides a way to integrate biophysical and socioeconomic processes with empirical quantification of physical stocks and flows in social-ecological systems. Analysis of metabolism differentiates between natural and socioeconomic drivers. Social-ecological models integrate both economic and ecologic dynamics by combining statistical social field data with historical physical resources to reconstruct past system states [37, 38]. These same models can then be combined with agent-based models [39] to understand the interplay between actors' decisions and biophysical flows.

Box 3.1 Urban Systems

The ecology of urban ecosystems can be thought of from a systems perspective where ecological effects of land use change, spatial distribution of resources (abiotic and biotic) or population (biotic), and whole system metabolism (energy flows) are considered (Fig. 3.1). Examples of biophysical forces/drivers could include:

1. Flow of energy
2. Cycling of matter
3. Flow of information [41]

These forces exert influence on five major patterns/processes:

1. Primary production (energy by plants from photosynthesis)
2. Populations (growth or decline)
3. Organic matter (raw food)
4. Nutrients (available food)
5. Disturbance (human and natural)

Box 3.1 (continued)

In turn socioeconomic drivers affect the previous biophysical processes via:

- Information flows
- Cultural values and institutions
- Economic systems
- Power hierarchies
- Land use and management
- Demographic patterns
- Designed or built environment

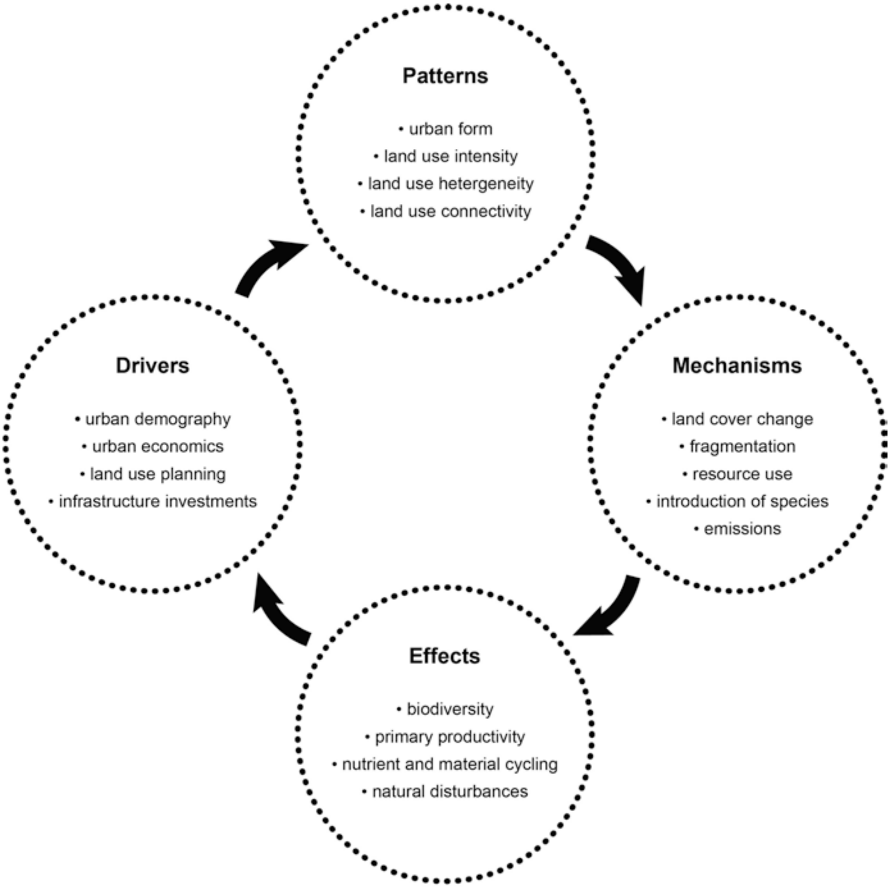


Fig. 3.1 Urban ecosystem patterns, drivers, mechanisms, and effects. Redrawn from Alberti [40], p. 175

One needs, therefore, integrative mechanisms for including and tracking socioeconomic drivers within urban systems. We also need to know how such processes and patterns affect urban environmental quality, quality of life, human health, and ecological health. For some key definitions, see those provided in Box 3.2:

Box 3.2 Some Basic Definitions
The following are definitions of key terms that will be heavily utilized within this chapter:

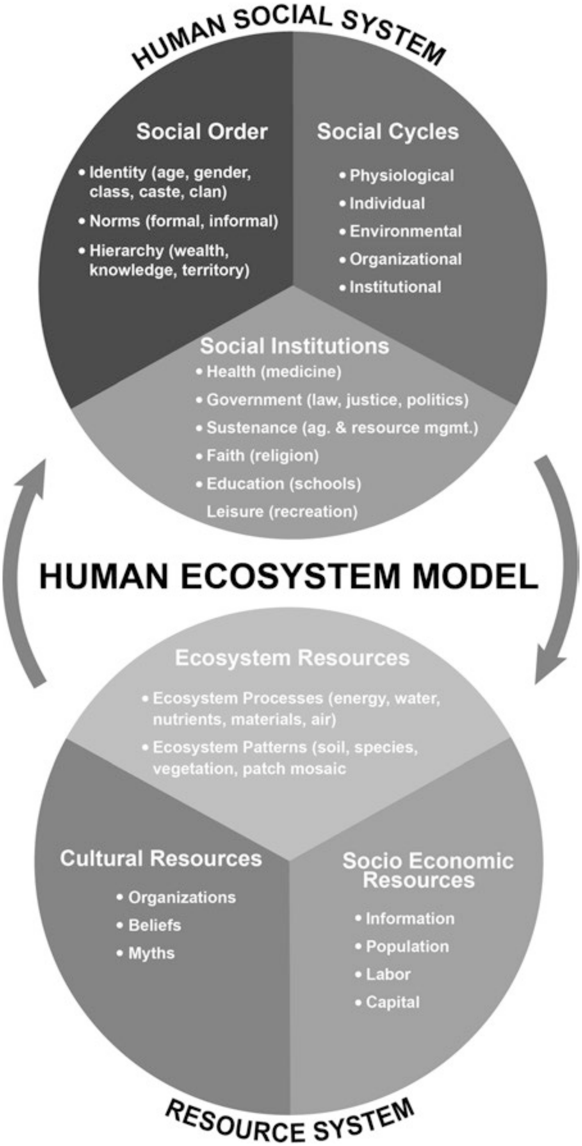
- *Health* is the state of complete physical, mental, and social well-being.
- *Well-being* is material security, personal freedoms, good social relations, and physical health [42].
- *Healthy ecosystems* are resilient to stress and degradation and maintain their organization, productivity, and autonomy over time [43, 44].
- *Ecosystem services* are the delivery, protection, and/or maintenance of environmental goods and benefits that humans obtain from ecosystem functions [42, 45].
- *Green infrastructure* can be considered as all-natural, seminatural, and artificial networks of multifunctional ecological systems within, around, and between urban areas, at all spatial scales (p. 169 in [46]).
- *Social-ecological systems* are complex integrated biotic and abiotic structure and functions that emerge through the continuous interaction of human societies and ecosystems [47, 48].

3.2 Frameworks for Integrating Social Science with Urban Ecosystems

So what conceptual frameworks have been developed that link urban ecosystems, human, and ecological health? We will explore this question in the next section. There appear to be four conceptual frameworks that combine both the sociological and ecological realms that have been applied to urban ecosystem studies to date: (1) the Human Ecosystem Framework from the Baltimore Long-Term Ecological Research (LTER) project, (2) environmental effects on mental and physical human health, (3) ecological services to people from biophysical systems, and (4) models of livability/quality of life and environmental justice/equity.

The *Human Ecosystem Framework* (Fig. 3.2) is derived from the Baltimore Urban Ecosystems Long-Term Ecological Research (LTER) study [50–53]. This is an interlinked model with a human social system and an ecological resource system. Note that this framework includes social institutions, social cycles, and social order in the upper part of the model as well as cultural resources within the resource

Fig. 3.2 The human ecosystem model. Redrawn from Grove et al. [49], p. 170



system in the lower part of the model. Compare this with Fig. 3.1, which is primarily an ecological model without social processes included. This model has been adapted and utilized by Grimm et al. [54] to analyze variables, interactions, and feedbacks to urban ecosystem social aspects from land use change in Phoenix, Arizona.

The second conceptual framework addresses *environmental effects* on *human mental* and *physical health*. There has been an increasing amount of work linking urban green space to mental and physical health plus community relationship

Table 3.1 Models and theories linking ecosystem and human health

Author	Model/theory	Environmental aspect	Human health aspect
Freeman [55]	Mental/physical health effects	Physical, social, and cultural factors	Nervous system and illness
Henwood [56]	Psychosocial stress and health	Poor environment	Chronic anxiety, stress, and high blood pressure
WHO [57]	Architecture of health	Environmental, cultural, and socioeconomic factors	Community, lifestyle, and hereditary factors
Paton et al. [58]	Healthy living and working model	Environmental, cultural, and socioeconomic factors	Living and working conditions
Macintyre [14]	Basic needs framework	Natural environment and resources and landscape	Health—all aspects

Adapted from Tzoulas et al. [46], with permission from Elsevier

improvement. A variety of model theories, physical environmental factors, and related human health domains have been investigated (Table 3.1). Green urban space and biodiversity may have value for improving mental and physical health for urban residents, but much works need to be done to further demonstrate such linkages and benefits.

The third construct is the Millennium Ecosystem Assessment [42], which assesses global ecosystems' changes and impacts on human well-being [59]. This approach includes a conceptual framework linking some *ecosystem services* and *human well-being* through socioeconomic factors. Ecosystem services are grouped into four categories: provisioning, regulatory, supporting, and cultural services; these services provide for human well-being within five categories, security, access to basic resources, health, good social relations, and freedom of choice.

The fourth construct is a comprehensive model for *livability* and *quality of life*, which was synthesized by van Kamp et al. [60] and Circerchia [61]. This model illustrates a complex interplay of factors affecting quality of life including personal, social, cultural, community, natural and built environment, as well as economic factors.

The fifth and final framework is that of *environmental justice* [1, 62–65]. The US EPA defines environmental justice as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies"[1] (see Chap. 14). The environmental justice movement is a response to the siting of undesirable facilities, which cause negative social and environmental conditions in neighborhoods that traditionally have had no participation in the decision-making process. This is a framework that addresses two major equity issues for urban residents: (1) undesirable environmentally impacting projects in low-income neighborhoods and (2) access to green space that fosters mental and physical health and well-being.

All of the above are examples of approaches that can be incorporated within long-term coupled *social-ecological* research models [48] to (1) investigate changes

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[1] https://www.epa.gov/environmentaljustice.

Table 3.2 Studies of green space/nature impacts on human health

Author	Type of study	Human health findings
Kellert and Wilson [66]	Interdisciplinary study synthesis	Innate need > contact with biodiversity > psychological well-being
Takano et al. [67, 68]	Epidemiological	Urban green space > longevity
De Vries et al. [69]	Epidemiological	Urban green space > better health
Payne et al. [70]	Questionnaire and diary	Urban park users > perceived health, physical activity, and relaxation
Kaplan and Kaplan [19], Hartig et al. [18], and Wells [23]	Experimental	Natural views restore attention fatigue, quicken recovery, and cognitive performance
Ulrich [71] and Ulrich et al. [22]	Experimental	Natural views provide relaxation, increase positive emotions and stress recovery
Faber-Taylor et al. [72]	Experimental	Reduced symptoms in children with ADD
Kuo [21] and Kuo and Sullivan [73]	Experimental	Green views > crisis management, effectiveness, reducing mental fatigue, less aggression
Korpela [74, 75], Korpela and Hartig [76], Korpela et al. [20], and Newell [77]	Survey	Visit favorite natural places > regulation for self-expression
Kim and Kaplan [78]	Survey	Residential natural features enhance sense of community
Palmer [79], Smardon [80], and Westphal [81]	Survey	Green space personal aesthetic preference and sense of community

Adapted from Tzoulas et al. [46], with permission from Elsevier

in the state of the environment; (2) analyze societal pressures on ecosystems and the forces driving them; (3) propose measures that might alleviate these pressures; and (4) assess the effect of ecological change on society (e. g., climate change).

3.3 Social Science Empirical Studies of Urban Ecosystems

There have been a number of social science empirical studies that address the links between socioeconomic status, health, and physical environmental attributes. These studies can be characterized as epidemiological studies, experimental studies, and survey-based studies (Table 3.2). Positive aspects of green space epidemiological[2] studies include positive relationships between urban green space and longevity, health, well-being, and sense of community. Negative aspects of neglected green space include fear of crime [73, 82, 83] and increased habitat and range for disease carrying vectors [80, 84, 85]. Benefits from urban green space experimental studies include passive viewing, reduction of psychophysiological stress, health recovery

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[2] Meaning studying populations over time and area.

time, improved attention functioning, lowered blood pressure, and lessening aggressive tendencies. In general green space within urban ecosystems constitutes significant public health benefits [78, 86]. Survey studies show urban green spaces are favorite places to regulate feelings, emotional release, restorative experiences, and reduction of negative feelings. Those with health complaints choose vegetated green spaces as their favorite places [87], so biodiversity tied to environmental quality is important for health restorative purposes [88, 89]. The lack of urban green space within urban areas could also, on the reverse side, cause increased mental and physical health problems for urban residents.

3.4 Social Benefits from Urban Green Space

There has also been a body of work that has addressed the social benefits of green space—especially social cohesion and other social benefits. These other social benefits are publicly accessible green space allowing urban residents to interact with each other without physical or psychological restrictions, allowing recognition of residents, allowing group social contact, providing information and/or inspiration, and allowing contact between diverse groups and individuals (Table 3.3).

3.5 Urban Ecosystem Social-Ecological Approaches

A number of recent studies have attempted to link social-ecological drivers to spatial and temporal changes in ecosystem structure (Table 3.4). Two of these, for example, have used the Human Ecosystem Framework discussed earlier [51–53, 107] combined with spatial or gradient analysis, which cuts through a spectrum of land use/vegetative cover types from natural areas to center city. Scholars are working with such studies so that we can better determine which factors contribute to more optimum planning and decision-making strategies to make urban ecosystem more sustainable and promote both ecological and human health.

Table 3.3 Social functions of urban green space

Authors	Social functions
Burgess et al. [90], O'Brien and Tabbush [91], and Ward Thompson et al. [92]	Publicly accessible green space allowing social interactions
Carr et al. [93], Gehl [94], Greenbaum [95], and Kou et al. [82]	Social integration and recognition
Burgess et al. [90], Gobster [96], Gomez [97], Ho et al. [98], and Smardon [99]	Group social contact
Gehl [94] and Westphal [81]	Providing information and inspiration
Burgess et al. [90], Gobster [100], and Swanwick et al. [5]	Contact between diverse groups
Kweon et al. [101] and Rodgers [102]	Improving inclusion of individuals

Table 3.4 Urban ecosystem social-ecological study approaches

Author/place	Type of study	Key variables and concepts
Alberti [40], Seattle, WA	Simulation model with demographic, economic, and policy scenarios	Quantify spatial and temporal variability in environmental stressors
Andersson [103, 104], Stockholm	Qualitative study of management practices connected to ecological services	Underlying social mechanisms, institutions, local knowledge, and sense of place
Circerchia [61]	Indicators > quality of life	Land supply and demand, territorial loading, equilibrium, and critical population mass
Dow [61], Columbia, SC	Gradient analysis	Land use, land management effort, historical context
Grove et al. [52], Baltimore LTER	Vegetative cover vs. social factors	Population, lifestyle behavior, and social stratification
Pickett et al. [53], Baltimore LTER	Social-ecological path and dynamics special mosaic	Resiliency, ecological, and social functions
Redman et al. [47]	Social-ecological systems	Core social science research
Rees [105, 106]	Human carrying capacity/foot print analysis	Social carrying capacity

Some of these studies have looked at major socioeconomic drivers such as Alberti in Seattle [40], Rees in British Columbia [105, 106], Dow in Columbia South Carolina [108], and Circerchia [60]. Others are more focused on underlying social-ecological context factors that correlate with physical landscape change such as the work of Andersson [103, 104] in Stockholm and Grove et al. [107] and Pickett and Cadenass [52] in the Baltimore LTER. These relationships are important if we are to both understand urban ecosystems and social factors that are important to sustainability planning. The next section will include a review of sustainability planning approaches for urban ecosystems.

3.6 Short History of the Sustainable Cities Movement

Environmental consciousness began to increase after the first United Nations (UN) Conference on the Human Environment held in Stockholm in 1972. Urban environmental agendas that evolved from this conference were named the *Brown Agenda* [109] by the international development agencies such as the World Bank. Before this, international attention related to environmental issues had been focused on the rural environment, particularly with respect to the development and issues of resource extraction the Brown Agenda for the first time acknowledged the environmental issues faced by cities, particularly those of the developing South, from uncontrolled factory and auto emissions and use of low-grade fuels, lack of sewage treatment and clean water supplies, inadequate solid and hazardous waste facilities, etc. The second UN Conference on Environment and Development (UNCED) was held in Rio de Janeiro in 1992 and the subsequent UN Habitat Conference held in Istanbul in 1996, developed the concept of *Sustainable Cities*. The Rio Conference developed the “Green Agenda” to address pressing issues of deforestation, resource depletion, global warming, biodiversity, and pollution. The Sustainable Cities concept merged the *Brown* and *Green* Agendas plus implementing Agenda 21 in an urban context thus launching the Sustainable Cities Programme (SCP).

The Sustainable Cities Programme (SCP) is a joint UNCHS/UNEP program. It works toward the development of a sustainable urban environment, building capacities in environmental planning and management, while promoting a broad-based participation process. At the moment the SCP is a locally focused program, in that there is some national, regional, and global support for activities and programs at the city level. SCP provides a framework for linking local actions and innovations to activities at the national, regional, and global levels. Global networks such as the UN Programs and the International Council of Local Environmental Initiatives (ICLEI) work in coordinated fashion. The primary role of SCP is at the city level, where the program applies more than 95% of its resources in the first 5 years. The SCP intent is to bring together all the stakeholders whose cooperation is required (1) to clarify environmental issues, (2) agree on joint strategies and coordinate action plans, (3) implement technical support and capital investment, and (4) institutionalize continued environmental planning and management. The program stresses that full realization of a city's potential contribution to development is often obstructed by severe environmental degradation. Such degradation threatens (1) economic efficiency in the use of scarce resources, (2) social equity in the distribution of development benefits and costs, (3) sustainability of hard-won development achievements, and (4) productivity in the urban economy in provision of goods and services. Other international programs that promote biodiversity within urban areas are of three types, (1) those that are focused on making cities more sustainable under Local Agenda 21, (2) those that assess urban biodiversity and urban biosphere reserves, and (3) protection of green space function [3].

We will focus on implementation of Agenda 21 programs. A review of all of these programs is found in [3]. There now exist a large number of urban sustainability programs under the aegis of Local Agenda 21 (see Box 3.3)

Box 3.3 International Urban Sustainability Programs

- Best practices database in the UN-Habitat at http://www.bestpractices.org.html.
- Caretakers of the Environmental International—a global network of teachers and students active in environmental education at http://www.caretakers.boker.org.
- Cities for Climate Protection (CCP) is a worldwide action agenda for reduction of greenhouse gases and energy conservation at http://wwwiclei.org/ccp/. This program includes over 500 cities worldwide.
- The International Center for Sustainable Cities promotes sustainability in cities worldwide through practical demonstration projects using Canadian expertise and technology at http://www.icac.ca/index.html.

(continued)

Box 3.3 (continued)

- The International Institute for the Urban Environment is establishing a network on MILU (Multi-functional Intensive Land Use) in cities in Europe for 2005–2007 at http://www.urban.nl.
- The Urban Environmental Forum and UN Human Settlements Programme are a global coalition of cities and international support programs working on the urban environment at http://www.unchs.org/programmes/uef/.
- The UN Habitat Human Settlements Programme and Sustainable Cities Programme at http://www.unesco.org/mab/urban/. This program includes at least 40 cities worldwide.
- The Virtual Library on Urban Environmental Management includes projects, features, and themes addressing urban environmental management at http://www.gdrc.org.
- The WHO Healthy Cities program includes some 1500 localities.

Almost all these programs are meant to support implementation of Local Agenda 21 from the UNED 1992 Rio meeting and are locally tailored for municipal or regional sustainable development planning. Chapter 28 of Agenda 21 articulates the process by which local sustainable development plans are to be developed and implemented. Chapter 28 does not specify what local plans should include but is process-oriented for local planning. It stipulates that development of local plans should address local needs and concerns through education and mobilization of local citizens. At least 5300 local authorities from European countries have Agenda 21 action plans, but only a little over 100 municipalities have such action plans in North America [3].

One reason for the large number of Local Agenda 21 sustainability plans in Europe is the Aalborg Charter, known as the Charter of European Cities and Towns Towards Sustainability that was developed to provide more detailed guidance for sustainability planning [3]. Part II of the Charter provides specific guidance for sustainability planning with these steps:

- Recognition of existing planning and financial frameworks as well as other plans and programs
- Systematic identification, by means of extensive public consultation of problems and their causes
- The prioritization of tasks to address identified issues
- Creation of a vision for sustainable communities through a participation process involving all sectors of the community
- Consideration and assessment of alternative strategic options
- Establishment of long-term local action plan toward sustainability, which involves measurable targets
- The programming of the implementation of the plan, including the preparation of the timetable and statement of allocation of responsibilities

- Establishment of systems and procedures for monitoring and reporting on implementation of the plan

What is significant here is the link of contextual social science theory that ties individual perceptions, needs, values, and knowledge to the sustainability planning process via intensive participation of concerned stakeholders. This is the essence of Local Agenda 21 planning process.

3.7 Decision-Making and Social Science

Campbell [1] warns that in the North American context, sustainable development cannot be reached directly but rather only through a sustained period of confronting potential conflict areas (Fig. 3.3). These areas revolve around whether to *grow* the economy and how to distribute growth fairly and not degrade the ecosystem. Between equity/social justice and economic development, there is the property conflict. Between equity/social justice and environment, there is the development conflict; and between economic development and environmental protection, there are often resource conflicts. Campbell [1] proposes that tools will be needed to resolve such conflicts as redefining the language of the conflicts, land use/design innovation, and bioregional approaches.

The more general issue—drawing from contextual social theory—is that cities are diverse, and often a contested landscape, especially when it comes to achieving sustainability, because we often have multiple values, actors, and perspectives that can lead to conflict. Conflict is not inherently bad but needs to be worked through

Fig. 3.3 Sustainability planning conflicts. Redrawn from Campbell [1]

with methods such as conflict resolution and mediated modeling that include a contextual social theory approach as defined in Sect. 3.1 earlier.

Such potential conflicts are reflected in the Syracuse NY Onondaga Lake cleanup. Under legal requirement to reduce sewage outflows to the lake during storm events, the Onondaga County Executive decided that instead of capturing combined sewer overflow (CSO) outflow (see Chap. 6, Fig. 6.2) and directing it to expensive-to-build substation plants for treatment, the county instead would look at "green infrastructure" as an alternative. The strategy would be to slow urban runoff using permeable pavement, drainage swales, rain gardens, rain barrels, and more tree plantings. The question remained whether such "green infrastructure" would be acceptable to city residents. We know from past research [79, 80] that some urban residents do not like shade trees and shrubs because of leaf litter, shading their gardens, or facilitating illegal activities. To determine the factors that might affect urban residents' attitudes and preferences toward "green infrastructure" [26, 80, 110], social scientists turned to theory regarding decision-making behavior [111] and prospect theory or how people make decisions with risk considerations [112, 113]. From this information a series of focus groups and a survey designed to "surface" attitudes, preferences, and values regarding green infrastructure and its relationship to environmental service provisioning and quality of life for urban residents were designed [114]. Additionally residents' willingness to implement green infrastructure measures and why they would be interested in doing so were assessed [115].

3.8 Case Studies

The following case studies illustrate some of the previously mentioned benefits and functions of urban ecosystem green space/infrastructure. They also illustrate decision-making issues and social processes involved with implementation as well as social science research roles.

Case Study 1: Managing Stockholm's National Urban Park—Role of Social Network Structure

Key Sources: [116, 117]

The National Urban Park is a 27 km mixed wooded area close to the city center of Stockholm, Sweden (Fig. 3.4). The area's high biodiversity and its capacity to generate ecosystem services are tightly linked to long-term use of the park by various user groups in the form of allotment gardens and by royal management stretching back hundreds of years. The proximity to Sweden's political, administrative, and business center results in significant exploitation pressure from municipalities, state, and building companies that have accelerated since the 1990s. Although there had been earlier protection movements, it was not until 1990, in reaction to a new set of plans for development, that the EcoPark movement emerged [116]. Such a movement began as part of a citywide protest against a larger set of motorways and other developments planned for Stockholm.

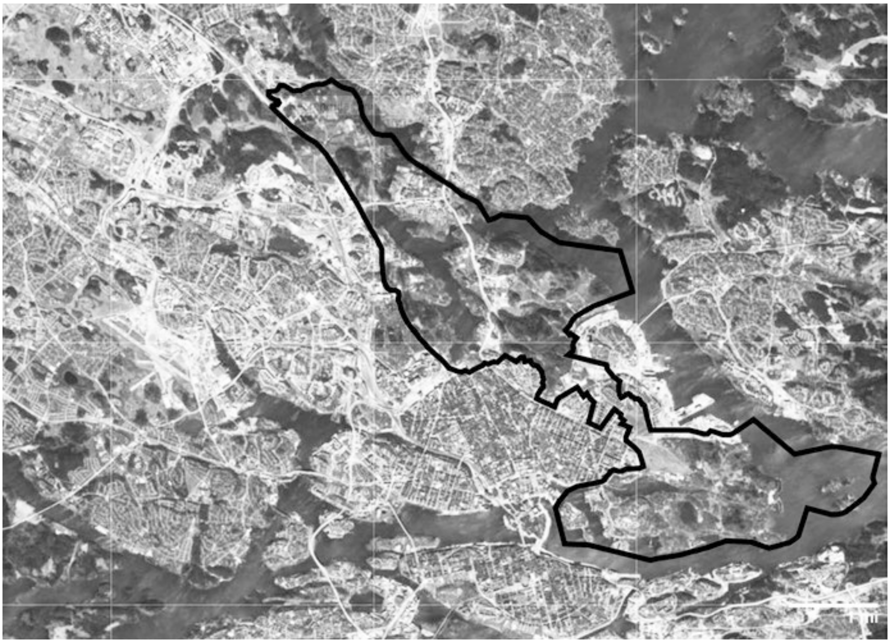

Fig. 3.4 Map of Stockholm Royal Park system. (Redrawn from https://www.visitstockholm.com/see%2D%2Ddo/attractions/royal-national-city-park/ and https://en.wikipedia.org/wiki/Royal_National_City_Park)

Despite this movement's success in protecting the park area through the 1995 legislation, development plans continue to be made, and this movement continues to mobilize. To combat this, the protection movement first constructed a novel vision of the area by framing the set of park areas in a novel way. Such a framing process stretched the movement's identity over a greater spatial area, which was important in order to mobilize a diverse set of organizations that were active in different parts of the EcoPark. This was done by bringing all the different areas of the park under one appealing name the "EcoPark" and by then creating a narrative to explain how these areas had been treated prior to 1990 and their interconnections [117]. This vision and story were facilitated by the abundance of artifacts associated with the area, largely due to its royal history. Both cultural artifacts (planned English-style parks, sculpture, castles, buried sites, runestones, etc.) and scientific artifacts from conservation biology (e.g., reports on core buffer zones and species dispersal corridors) were employed to create "a protective story." In 1992 some 22 organizations created an umbrella organization. The Alliance of the EcoPark brings together some 50 member organizations.

The second part strategy used to build the "protective story" was the use of multiple methods to engage people's interest such as artist's galas, exhibitions, and lobbying. These creative activities created a narrative and graphic image that moved the political issue of the park to the national level, thus overriding the strong powers of the local municipalities within Greater Stockholm. In 1995 they were successful in getting the protective law of the National Urban Park passed.

According to Ernston et al. [116] in establishing the law, the EcoPark movement not only defined and constructed the identity of these green Stockholm areas but also transformed the governance structure. Municipalities were forced to collaborate across borders, which opened ecosystem management up over an extensive landscape. Second, the Country Administrative Board was given the right to override the strong Swedish planning monopoly. This opened up new options for influencing park management decision-making. A detailed network analysis by Ernston et al. [116] further documents such opportunity creation and the transformational change of park management governance structure.

Case Study 2: Exnora—Community-Based Waste Management in Indian Cities

Source: Smardon [3]

"One of the most intimidating challenges in rapidly growing urban ecosystems is waste management (see Chap. 10), and in Indian cities we see some of the most rapidly growing urban ecosystems in the world (see Chap. 1). Solid waste management (SWM) projects dominate among environmental management efforts in India. Some local governments have tried to elicit the support of communities, NGO's and private companies to help solve this pressing issue. In both Ahmedabad and Mumbai, a private company is contracted to compost part of the city waste. In Mumbai, Bangalore and Chennai NGO's are involved in the collection and disposal of waste on behalf of city government. In Pune, local government has encouraged housing colonies to decompose their organic waste by composting, and in Rajkat, the city government by itself is efficiently collecting solid waste [118]. All these efforts began in the 1990s.

In Ahmedabad, the World Bank donated Rs. 38 million to modernize SWM, and collection consequently increased three to four times, documented by case studies where NGO's and community groups participated in composting garbage for only a few hundred households [118]. In Andhra Pradesh, the municipal administrator contracted out solid waste collection to a woman's group formed under the government via India's Golden Jubilee Urban Employment program [119]. This is a holistic approach whereby local communities and government are addressing environmental and poverty issues together.

Against this background, one experiment to manage SWM was undertaken by a non-governmental service organization called Exnora (Fig. 3.5), which started in Chennai, India1989 when citizens, concerned with deteriorating environmental conditions, drew up an action plan to collect garbage. Exnora stands for *ex*cellent, *no*vel and *ra*dical ideas to engage those who created an environmental problem to participate in solving it. New containers were placed in the street and an awareness campaign was organized. The rag pickers, renamed city-beautifiers, were given loans by Exnora to purchase tricycles for door-to-door garbage collection and street cleaning. They received monthly salaries from the residents from which they repaid

Fig. 3.5 Exnora International group photo. Image Source: https://commons.wikimedia.org/wiki/File:ExnoraY.jpg from Wikipedia commons, with gracious permission of Exnora Founder, Dr. M. B. Nirmal

the loans. Today the city has 1500 Exnora units, each serving 75,000 families or 450,000 people.

Many Exnora participants have now branched into other environmental activities such as, monitoring waterways, desilting canals, planting trees and harvesting rainwater. They also run environmental programs in schools and public information campaigns on the environmental impact of industrial development, upgrading slums and converting waste into useable compost. Exnora projects are multi-sectoral and address a wide range of issues [120].

Other cities in India have started similar activities. In Vadodara City in the western Indian state of Gujarat, the Citizens Council and a local NGO, started garbage collection in 1992, engaging local unemployed young people and rag pickers in garbage collection at a monthly salary of Rs. 300–400 ($7–10) paid by the residents. Recycled waste (paper, plastic, metal, etc.) is carried away by rag pickers and sold. Degradable waste is composted, and the remaining material is dumped into a landfill. With the support of the United States Agency for International Development (US AID), this project has been extended to cover 20,000 households or 100,000 People [121]. Similar experiments are being carried out in some areas of Delhi with input of local NGO's such as Aatavan [122].

This case study is an example of the need for a systems management approach to SWM, combined with micro-finance and appropriate technology that works in a developing country context. Use of NGO type organizations for these purposes is also replicable to many developing country urban ecosystems" ([3], pp. 130–131).

3.9 Conclusions and Summary

In summary this chapter contains a review of the array of social science theory that is applicable to studying urban ecosystems from early *reductionist* to the more recent *contextual* theories. Next, conceptual frameworks of linking social theory-grounded approaches to urban ecosystem theories are covered including the Human Ecosystem Framework, environmental effects on mental and physical health, ecosystem services, models of livability and quality of life, and environmental justice equity. A number of social science empirical studies that were reviewed showed human health and social benefits from urban green space. Urban social-ecological studies were reviewed as well as a history of the Sustainable Cities Movement and Agenda 21 for sustainability planning. Finally, there is a discussion of decision-making and social science as it affects sustainability and urban ecosystem decision-making.

According to Haberl and others, there have been at least four major approaches that hold promise for analyzing urban ecosystems from a long-term perspective [48]. These include (1) an urban ecosystem's *metabolism*, (2) *land use/landscape spatial* patterns, (3) *urban ecosystem governance*, and (4) the role of *communication and knowledge*. Two case studies were presented illustrating these approaches: Managing Stockholm's National Urban Park is first a story of land use, then communication and knowledge, and finally governance. To conserve an area for its historic land uses, they used creative ways to communicate the story to the public and enhance community knowledge, which in turn led to citizen pressure that brought about changes in governance. The explicit study of *communication and knowledge* formats within long-term interactions between nature and society allows assessment of transformation including the role of actors and networks. Study of knowledge and communication allows us to understand mechanisms leading to organizational forms including noninstitutional power structures [123]. By involving stakeholders, this leads to transdisciplinary research approaches, which may in turn lead to new ways of conceptualizing the interaction process.

The second case study is the Exnora community-based waste management programs implemented in India where different interventions and the results of reduction and or reuse of solid waste through a collaboration of different actors and different interventions changed the *urban metabolism*, by providing jobs and income for people, among several benefits realized. It is also, however, an example of how a social-ecological system approach addresses land use as less area for landfills will be required, and governance as often governments have enlisted private groups to help solve the SWM problem, and how communication and knowledge were implicit to the transformation from filthy city streets where garbage accumulated to clean ones by getting people informed and thus involved in the disposal, recycling, and reuse efforts.

It is our hope that this chapter has helped you see how the concept of *urban metabolism* provides a way to integrate biophysical and socioeconomic processes;

to analyze social-ecological flows of energy, wastes, and other human resources; and to thus integrate both economic and ecologic dynamics.

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Part II
The City in History

Chapter 4
Scale and Metabolism in Ancient Cities

Joseph Tainter

Abstract Ancient cities were like modern ones in some important ways and unlike them in others. Both have consisted of dense agglomerations in which people live in ways that are unprecedented in human history. Despite their points of similarity, scale and metabolism distinguish ancient cities from modern ones. Using the examples of Athens, Rome, and Pompeii, this chapter explores how these cities appropriated energy sources, how they employed time-shifting of energy through debt, and how together these allowed ancient cities to grow but also constrained their scale, unlike sprawling cities of today.

Keywords Complexity · Energy · Exchange · Urban metabolism · Urbanism

4.1 Scale and Metabolism in Ancient Cities

Ancient cities were like modern ones in some important ways and unlike them in others. Both have consisted of dense agglomerations in which people live in ways that are unprecedented in human history. People in urban settings pursue diverse occupations, so that the economic system is complex. People pursuing diverse occupations require training, so there must be institutions for education and/or apprenticeship. Having many people living in proximity means that there will be disputes, thefts, assaults, and murders. Maintaining peace and order requires that there be an administration to provide policing and justice and punish offenders. It takes taxes to support these functions, which many people will try to avoid paying. The administration must have accountants, employees to enforce payment of taxes, and specialists in law. The administration must provide infrastructure—streets and public buildings and perhaps water and sanitation—and regulate the use of these. Ancient cities were usually unhealthy places, as many cities still are. Thus there must be medical services, and programs to train and certify medical practitioners. Cities often hold accumulations of wealth, which others would like to have. Ancient cities

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therefore had walls and military forces, requiring still more taxes. Modern cities achieve security by paying taxes to a nation state, which in turn provides protection. And both ancient and modern cities required the support of land areas larger than the settlement itself. Cities both ancient and modern could usually not grow enough food within their boundaries to support their populations. Every city requires a sustaining area, and the size of a city is linked inextricably to the scale or size of its sustaining area.

There is clearly no such thing as a simple city. Cities are complex systems. A city requires resources, most basically to sustain its population in its biological needs. It also needs resources to sustain its complex cultural, social, political, and economic systems. Just as a complex organism has greater metabolic needs than a simple one, a complex human society has a higher metabolic rate (throughput of resources) than a simple one. The products that an ancient city used were either sources of energy (food, fuel) or other things produced with energy. Metals, other raw materials, containers, building materials, draft animals, and so forth—all were produced with energy. Energy is the common denominator of urban metabolism. The metabolic requirements of ancient cities determined not only their size, but much else as well.

Despite their points of similarity, scale and metabolism distinguish ancient cities from modern ones. The largest city in the ancient world was Rome, which at its peak in the first century A.D. held about 1,000,000 people. Today that would be a city of only moderate size. Not only are cities today much larger than those of the past, they also draw on a global sustaining area. Whether it is electronics from East Asia, wine from France, or winter fruit from Chile, cities today draw their resources, products, and services from the entire world. No ancient city could have done so on the scale that we do today, although wealthy citizens of Rome were able to purchase spices from India and silk from China. Energy is the reason for these differences in scale and metabolism. Cities today are sustained by the subsidy of fossil fuels and to a lesser extent by nuclear power. Fossil fuels are of course the accumulation of past solar energy. Fossil fuels allow cities of today to reach levels of scale, metabolism, and complexity that were previously unimaginable.

Some ancient cities had subsidies, but none comparable to fossil fuels. In size and metabolism, they were limited by the energy of the sun. That is, they were primarily limited by *current*, *local* solar energy and had little or no access to energy from the past. As I will discuss below, some ancient cities did partly find ways around this limitation, but the limitation was nonetheless real. Solar radiation reaches the Earth's upper atmosphere at a rate of 19,400 calories per square meter per minute. Thirty-one percent of this is reflected or scattered, while 23% is absorbed in the troposphere or upper atmosphere. The remaining 46% (about 9000 calories) of the original solar radiation reaches the ground or near it. Then, 34% of this is reflected back by snow or clouds. Forty-two percent goes to heat land and water. Twenty-three percent drives the water cycle, evaporation and precipitation. One percent drives wind and ocean currents. Of those original 19,400 calories, 2.1% is available for photosynthesis. That is 400 calories per square meter per minute to support nearly all life on Earth, including everything that humans thought, did, and accomplished before we came to rely on fossil fuels. Of those 400 calories, the plant needs some for itself, so humans and other consumers actually get less. Cities were built, administered, embellished, walled, and defended on a fraction of 400 calories per square meter per minute. In contrast, a gallon of gasoline has 31,000 calories, the energy equivalent of a person working about 400 h.

A human being requires about 24 calories per second (100 W) on a continuing basis for metabolism. In an ancient city, the energy required for administration, maintaining order, public festivals, erecting buildings, constructing and defending walls, and so forth meant that the total metabolic requirements far exceeded those needed just to keep people alive. Most ancient cities were limited in population by the solar energy of the territories that they controlled. These territories were necessarily small. Attica, the territory of ancient Athens, covered only about 700 square miles. Athens at its height may have held about 250,000 persons (although, as will be discussed, not all of these were supported by the territory of Attica). For a Greek city of its time, Athens was unusually large. The much smaller Italian city of Pompeii, with about 8000–12,000 people, had a territory of less than 80 square miles. Why were ancient cities and their territories so small? The answer again comes down to energy, in this case the energy required for transport.

Iron laws of energetics dictated the small size of ancient cities. When energy is transformed from one form to another, as from grain to herbivores, about 90% is lost as heat. Land transport in the ancient world was mainly by ox-drawn cart. Oxen can pull loads up to three to four times their body weight. But oxen are biologically inefficient, requiring an extra energy conversion for their own metabolism. Oxen are also slow, plodding draft animals. This meant that, in the ancient world, land transport was expensive. Bulk commodities could not economically be transported very far. A wagon load of wheat would double in value with a land journey of only 300 miles. Land transport was so costly and inefficient that it was often impossible to relieve famines in inland cities, even if grain was plentiful in unaffected regions. Thus the territories of cities could not extend much beyond the distance within which grain could be efficiently transported to the city.

Meat production is biologically inefficient, for the same reason that oxen are. The main meat in ancient cities was pork, since pigs can be fed on scraps, they are relatively efficient energy converters, and they can walk to market as long as the market is not far away. Even still, meat was always expensive and figured regularly only in the diets of the wealthy. Most people subsisted on grain.

Cities situated on or near navigable bodies of water could often escape the constraint of transport. Ship transport, while risky and restricted to the sailing season, was comparatively economical. Transport by road was 28–56 times more costly than by sea. It was less expensive to ship grain from one end of the Mediterranean to the other than to cart it 75 miles. The largest cities of the ancient Mediterranean world—Alexandria, Antioch, Athens, Constantinople, and Rome—were all sustained by water transport.

Harvests often failed, and famine was a constant threat. The cities of the ancient Mediterranean rarely took extraordinary steps to protect their citizens from food shortages. Grain supplies were held and sold privately. The same men who controlled local wealth (which meant controlling land and grain) also controlled local governments. Civic authorities did try to prevent the hoarding of grain during shortages, or withholding it from the market, but rarely procured it for the public.

The rich gained prestige, though, through acts of public munificence, which could include distributions of food.

No city, ancient or modern, is an island. All are parts of larger systems that affect their metabolism. Ancient cities were usually embedded in political and economic systems that influenced their sizes. Cities grew and shrank as empires expanded and contracted. Patterns of trade also affected how many people a city could support. Slavery had much influence on the sizes of cities. These factors mean that cities cannot be discussed in isolation. They must be understood in the context of various social, political, military, and economic factors.

Fresh water and sanitation were often not provided in early cities or were minimal. Crowding meant that diseases spread quickly. Life expectancy was short. Cities had to be replenished by regular immigration from the countryside. Usually country dwellers found cities attractive and moved in voluntarily. Yet sometimes this was not enough to keep a city populated. For example, after an earthquake in 740 A.D. and plague in 747–748, Byzantine emperor Constantine V (741–775) found that Constantinople was insufficiently populated. His solution was to force people to move into the city from mainland Greece and the Aegean Islands.

Much of the life of ancient cities is lost to us, being little documented. Modern cities grew on top of ancient ones, so that archeological study of past cities is difficult. Fortunately, we have significant knowledge of a few. Three will be discussed here: Athens, Rome, and Pompeii.

4.2 Case Studies

4.2.1 Athens

Ancient censuses counted only adult male citizens, but from these we can estimate total populations of free citizens. Slave populations are harder to calculate, although they were often substantial. Athens in 431 B.C. may have held 160,000–172,000 citizens. In the fourth century B.C., after decades of war and loss of her empire, the citizen population may have stood at 84,000–120,000. Athens illustrates how the scale and metabolism of an ancient city were influenced by broader political and economic factors.

About 35–40% of the land in Attica, the territory of Athens, was arable. Biennial fallow was common, so in any year perhaps only 20% of the land was worked. This would have been about 140 square miles. It is estimated that the wheat harvest failed 28% of the time. Barley, which is hardier, would have failed only about 5.5% of the time. Yet wheat was the preferred food, and barley (which cannot be made into bread) was used to feed animals, slaves, and the poor. Counting slaves and noncitizens, Athens' population in 431 B.C. may have been about 250,000, which exceeded what Attica could support. Much grain needed to be imported.

To support her population, Athens needed to find ways to access solar energy beyond that falling on Attica. This meant having energy surrogates that could be exchanged for grain. An energy surrogate is something of value that is ultimately produced from energy, can be used to purchase or fabricate the products of energy, but does not itself satisfy human or cultural metabolic requirements. Money is the most common energy surrogate. Other valuables serve similarly. Time and labor are also energy surrogates. Athens used time and labor to produce energy surrogates in the form of pottery for export. These pottery vessels were artistically accomplished and highly desired (as they still are today). They were traded widely, and more than 40,000 specimens and fragments survive to this day. An export economy allowed Athens to secure the solar energy of other lands.

Part of Athens' fame in the ancient world and today came from her victory over the Persians at Marathon in 490 B.C. Just a few years later, in 483 B.C., Athens found great deposits of silver in the south of Attica. With this wealth Athens built a fleet of warships and used these to defeat Persia again at the Battle of Salamis in 480 B.C. Athens then freed the Greek cities of Asia Minor from Persian rule and, to prevent the Persians from returning, formed a league of cities of the Aegean Sea.

But the cities of this league soon found that they had traded one master for another. The league quickly became an Athenian empire. Tribute was imposed on these cities, and more silver poured into Athens. The population swelled as Athens became wealthy and attracted artisans and merchants. Grain was imported from the nearby island of Euboia, but also from distant sources in North Africa and the Black Sea. The navy protected these trade routes. The silver coins used to pay for Athenian imports are found throughout the Eastern Mediterranean and beyond. They were the primary trade coins of the fifth century B.C. and most of the fourth. Athens used silver, and the military power it purchased, as energy surrogates. These allowed it to support populations and create architectural wonders such as the Parthenon that would not have been possible with only the solar energy falling on Attica.

Athens fought Sparta in the Peloponnesian War, from 431 to 404 B.C. Due to Sparta's superiority on land, the citizens of Attica retreated behind Athens' walls, increasing the crowding in the city. Athens was struck in 430 B.C. with one of the most famous plagues of antiquity. The disease has never been clearly identified (epidemic typhus has been suggested recently), but its consequences were devastating. About 1/3 of the population within the walls died. The historian Thucydides left us a famous account of this plague, and it tells us about the risks sometimes posed by living in an ancient city.

> People in good health were all of a sudden attacked by violent heats in the head, and redness and inflammation in the eyes, the inward parts, such as the throat or tongue, becoming bloody and emitting an unnatural and fetid breath. These symptoms were followed by sneezing and hoarseness, after which the pain soon reached the chest, and produced a hard cough. When it settled in the heart, it upset it; and discharges of bile of every kind named by physicians ensued, accompanied by very great distress. In most cases also an ineffectual retching followed, producing violent spasms, which in some cases ceased soon after, in others much later. Externally the body was not very hot to the touch, nor pale in its appearance, but reddish, livid, and breaking out into small pustules and ulcers. But internally it burned so that the patient could not bear to have on him clothing or linen even of the very lightest description; or indeed to be otherwise than stark naked. What they would have liked best would have been to throw themselves into cold water; as indeed was done by some of

> the neglected sick, who plunged into the rain-tanks in their agonies of unquenchable thirst; though it made no difference whether they drank little or much. Besides this, the miserable feeling of not being able to rest or sleep never ceased to torment them. The body meanwhile did not waste away so long as the distemper was at its height, but held out to a marvel against its ravages; so that when they succumbed, as in most cases, on the seventh or eighth day to the internal inflammation, they had still some strength in them. But if they passed this stage, and the disease descended further into the bowels, inducing a violent ulceration there accompanied by severe diarrhoea, this brought on a weakness which was generally fatal. For the disorder first settled in the head, ran its course from thence through the whole of the body, and even where it did not prove mortal, it still left its mark on the extremities; for it settled in the privy parts, the fingers and the toes, and many escaped with the loss of these, some too with that of their eyes. Others again were seized with an entire loss of memory on their first recovery, and did not know either themselves or their friends [1].

Athens' method of food supply was mostly effective, and the city apparently suffered few famines. The ones that are known—405/404, 295/294, and 87/86 B.C.—were all caused by sieges. There were lesser but more frequent food crises in 338/337, 335/334, 330/329, 328/327, and 323/322 B.C. This was a time of upheavals, when Philip II of Macedon conquered Greece and his son, Alexander the Great, conquered Persia. The era of city-states was giving way to a new era in which Greece was but a part of large empires, being eventually incorporated into the expanding empire of Rome.

4.2.2 Rome

Rome began as a small settlement on the Tiber River in central Italy. Early in its history, it was perpetually at war with its neighbors, but the Romans became quite good at making war. Over several centuries they conquered people after people, until by the late third century B.C., they ruled most of Italy. By the first century A.D., they ruled all of the Mediterranean Basin and much of northwestern Europe. The size and metabolism of the city of Rome mirrored the scale and fortunes of the empire.

Various possible food shortages are recorded for Rome's early centuries, although we have few details. War was apparently the most common cause, and food crises became less frequent as Rome gained ascendancy in the fourth and third centuries B.C. The elected magistrates had the responsibility to secure and distribute emergency grain. The food supply of Rome became entwined with both politics and class struggles between the hereditary nobility (the patricians) and the common people (the plebeians).

The population of Rome grew from about 180,000 in 270 B.C. to 375,000 in 130 B.C. to 1,000,000 under Augustus, the first emperor (27 B.C. to 14 A.D.). As the city expanded, it was necessary to obtain grain from beyond Italy. Empire made this possible. By the mid-first century B.C., Sicily, Sardinia, and Africa all paid tribute to Rome in the form of grain.

In 123 B.C. the tribune Gaius Gracchus enacted a measure to provide for the inexpensive sale of grain to the lower classes of Rome. This was unparalleled in the history of Mediterranean cities. In 58 B.C. the charge for grain was dropped, and free grain became a right of poor citizens. Julius Caesar (46–44 B.C.) found 320,000 beneficiaries when he became Dictator, nearly 1 citizen in 3. He reduced this to 150,000, but the figure rose again. From Augustus (27 B.C.–14 A.D.) to Claudius (41–54 A.D.), about 200,000 heads of families received free wheat. By this time a major part of Rome's wheat supply came from Egypt, transported in large ships built for the purpose. Septimius Severus (193–211) added olive oil to the distribution. Aurelian (270–275) issued loaves of bread rather than wheat flour and offered pork, salt, and wine at reduced prices. A water mill was built in Rome in the second century A.D., and mills are known from other locations. Emperors also frequently handed out money to the people of Rome.

One consequence of making Egypt the principal supplier of grain is that Rome's supply depended on favorable sailing conditions. The good will of the population rode on suitable weather. In 6 A.D. there was a food crisis so severe that Augustus banished gladiators, and slaves for sale, to a distance of 100 miles from the city. Augustus and other officials dismissed their retinues, the courts recessed, and senators were allowed to leave Rome. The population was in a revolutionary mood until the spring of 7 A.D., when the Mediterranean opened for sailing and grain could again be imported.

A city of 1,000,000 needed to have stocks constantly replenished. Claudius (41–54 A.D.) developed a port at Ostia (Fig. 4.1) along the coast, and Trajan (98–

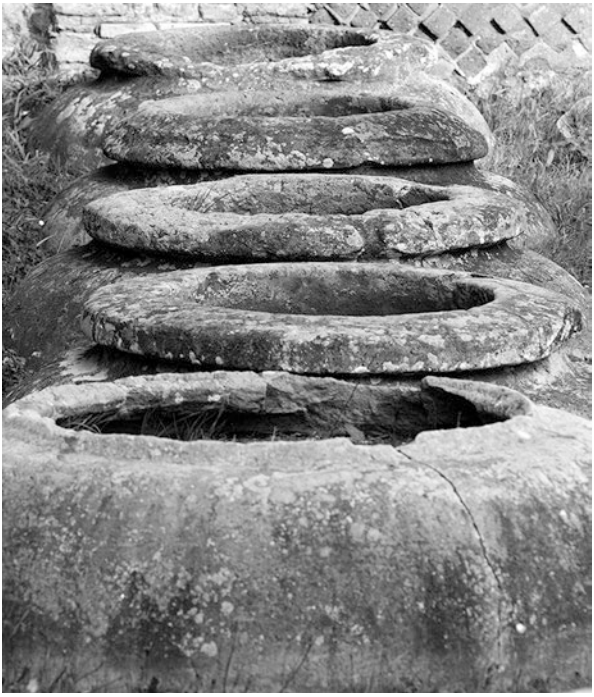

Fig. 4.1 Wine storage jars at Ostia. Photograph copyright Joseph Tainter

117) added another. From here grain and other commodities were loaded onto smaller ships, to be sent up the Tiber River to Rome.

Rome imported at least 2,000,000 gallons of olive oil annually. The site of Monte Testaccio in Rome gives an indication of the scale of imports to the city. Monte Testaccio is an artificial hill, composed entirely of discarded amphorae (large transport jars) (Fig. 4.2). It covers 220,000 square feet at its base and rises to a height of 115 ft. It was even higher in ancient times. Monte Testaccio is estimated to contain 53,000,000 amphorae, and as many as 130,000 per year were deposited in the second century A.D.

The streets of Rome were so congested during the day that the city had to be provisioned at night. Romans complained that the clatter of carts kept them awake. Bakers started to work in the middle hours of the night. Life for many Romans, though, might strike us as leisurely. The day was divided into 12 h of day and 12 h of night. Daytime hours were thus short in the winter and long in the summer. Breakfast (at least for those moderately well off) was a hearty meal: bread, cheese, milk, fruit, and perhaps some meat. It might include leftovers from the previous night's dinner. The morning hours were given to business. The poor tried to attach themselves to wealthy patrons and would present themselves at the patron's house in the morning. In a wealthy household, the mistress would oversee slaves in shopping, cleaning, cooking, gardening, and teaching the children. The master might walk to the forum to conduct business. The workday ended at noon, and shops closed for the day (Fig. 4.3). A quick lunch could be grabbed at a tavern (Fig. 4.4), but in the Roman day, it was a small meal.

Most of the afternoon was spent at the baths, where one would exercise, bathe, and get a massage. Time at the baths was spend socializing and was used to cultivate business and political opportunities.

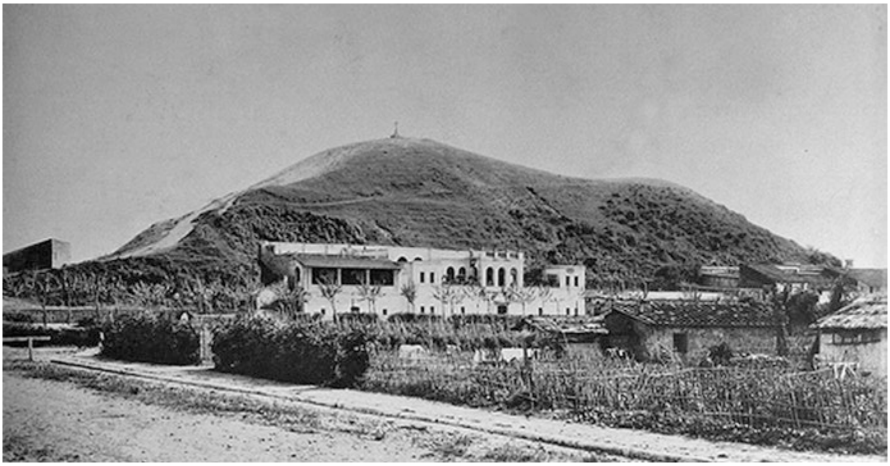

Fig. 4.2 Monte Testaccio, Rome, in the early twentieth century. Source: Wikimedia

Fig. 4.3 A street of Roman shops, Trajan's Market, Rome. Photography copyright Joseph Tainter

Fig. 4.4 A Roman lunch counter, Ostia. Photograph copyright Joseph Tainter

Dinner began in the late afternoon. The poor and those of moderate means would try to get invited to a wealthier person's house. (But one had to bring one's own napkin.) Because the only light came from oil lamps, and oil was expensive, everyone but slaves retired shortly after dark. Rome after dark was a dangerous place, and it was unsafe to venture out without a strong slave for protection.

Rome was well supplied with fresh water and had good sanitation. It was thus a healthier place than other ancient cities. Yet Rome's air was badly polluted, and crowding spreads disease. Up to the age of 10, 43% of boys would die but only 34% of girls. With adulthood, childbirth reversed the risk. A man who survived childhood diseases could expect to live 41 years, a woman only 29.

Compared with today's housing, the domiciles of even the wealthy were dark and drafty, hot in the summer and cold in the winter. Wealthy houses would have underground heating systems. These required a slave to be on duty all night to feed in charcoal. For safety, bedrooms lacked windows and locked from the inside.

The fortunes of Rome reflected the fortunes of her empire. A maximum population of 1,000,000 had apparently shrunk by the 270s when, after decades of crises, new walls were built for the city. A plague beginning in 165 or 166 A.D. had killed from 1/4 to 1/3 of the population. In 330 A.D. the emperor Constantine (306–337) diverted the Egyptian gain harvest to his new capital, Constantinople. Rome did not suffer from this diversion. By this time its population had declined to about 500,000 people, who could be supplied from North Africa. The population dropped to about 100,000 after the Goths sacked the city in 410. In 439 A.D. the Vandals conquered Roman Africa, and the city now had to be supplied by the produce of Sicily. The population stood at about 80,000 in 452. By the sixth century, Rome's population seems to have fallen to as low as 15,000. Rome now consisted of a set of villages clustered around churches. Rome could then be supplied, as it had centuries before, by production in its immediate vicinity. The popes took over distributing food.

4.2.3 Pompeii

Pompeii is the famous Italian city that was buried when Vesuvius erupted in 79 A.D. The city gives us an exceptional view of an ancient city at a moment in time.

Pompeii had a population estimated at 8000–12,000, although some estimates run as high as 20,000. Probably half of these were slaves. About 80% of expenditures would have been for food. Cereals were the main foods consumed, and they were produced near the city. High-value consumables, such as olive oil and wine, could economically be transported from farther away. Olive oil costs two to three times more per calorie than wheat. Pompeii's territory would have been about 77 square miles. The population of this territory is estimated at 36,000, so that the city held 25–33% of the regional population.

Residents of Pompeii engaged in 85 trades. Many of these were small-scale crafts catering to the local elites. Most commercial establishments were engaged in the preparation and sale of food. Bread was baked commercially, not at home. Textiles were a major industry.

Pompeii, like Rome, was well supplied with fresh water. Water arrived at a central point, from which it left in three branches. The largest branch went to pools and fountains, from which most people drew their water. The second went to the baths

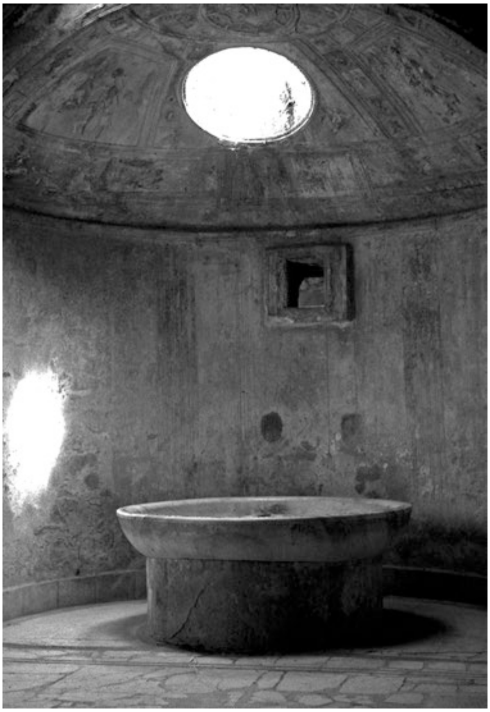

Fig. 4.5 The forum bath, Pompeii. Photograph copyright Joseph Tainter

(Fig. 4.5). A third pipe was for wealthy private users, who enjoyed the rare privilege of water piped into their homes. Fountains in Pompeii were nearly all located at intersections (Fig. 4.6). Most people lived within 88 yards of a fountain.

Of 1600 pottery vessels in one study, 29% were of Campanian (central-western Italian) manufacture, 35% were produced elsewhere in Italy, 23% came from the Eastern Mediterranean, 12% came from Gaul (France), and a few were from Africa. Thus more than 1/3 of these vessels came to Pompeii via water transport. Although Italy was a major wine producer, wine was also imported from the Aegean. Pompeii was noted for its fish sauce, a favorite of the day, yet nearly 30% of its fish sauce was imported. To obtain coins to pay Roman taxes, non-Italian provinces in the early empire had to sell goods to Italy. This may account for some of Pompeii's imports.

Much land within the city was devoted to agriculture. Grapes, olives, nuts, fruits, and vegetables were all produced within the city. These foods were primarily grown in less densely occupied parts of Pompeii, but there were also market gardens in more densely populated areas. Animal husbandry was practiced within the walls. Overall, productive gardens occupied 9.7% of the urban area and ornamental gardens another 5.4%. There was not a clear economic distinction between city and countryside.

Fig. 4.6 An intersection and fountain in Pompeii. Photograph copyright Joseph Tainter

4.3 Economic Exchange in Ancient Cities

Energy and the products of energy entered ancient cities from near and far, but primarily from nearby. Within cities, energy was differentiated into occupations and trades and into the raw materials that these required. Pompeii, as we have seen, had 85 occupations. Rome had over 200. The small town of Kōrykos, in southeast Anatolia (modern Turkey), had 110 different trades. Food sales at Kōrykos accounted for 15% of trades. (As at Pompeii, food would have amounted to about 85% of purchases. The bakers were busy.) Textiles (also important at Pompeii) accounted for 18% of occupations, building for 5%, pottery making for 10%, blacksmithing for 5 percent, various luxury trades for 13%, and shipping for 8%. Twenty-six percent of workers engaged in other trades.

Urban metabolism required that people exchange goods and services. How did they do so? Money functions well as an energy surrogate. Cities had, however, existed long before coins did, and even the smallest of early coins (from western Anatolia, about 650 B.C.) were too valuable to purchase basic commodities. A merchant could not make change if the smallest coin was worth a day's pay. Moreover, these smallest coins were minted in only limited quantities. This was because ancient governments did not mint coins to facilitate commerce. They minted coins to pay government obligations, the most common being soldiers' pay. Many early coins were worth a month's pay or more and so were useless for daily commerce.

(Bronze coins, suitable for small purchases, first appeared in Sicily in the fifth century B.C.)

Direct exchange could not have been a basis for commerce. A textile worker could not exchange a garment for bread if, on any given day, the baker did not need a new garment. The weaver needed bread every day, but the baker needed new clothes only occasionally. The textile worker in turn would not accept a knife from the blacksmith if he already had one. Nor would the baker. The builder could not exchange his product for anything needed on a daily basis. Yet somehow people in early cities made transactions, and satisfied their daily needs, without coins.

It appears that these transactions were accomplished through elaborate systems of credit and debt, standardized to a medium of constant value such as bars of metal. In ancient Mesopotamian cities, a shekel of silver (about 8.3 g) was established as the value of a bushel of barley. The silver existed as bars or lumps, but it was not used in most transactions. Debts were calculated in silver but did not have to be paid in silver. Temples and palaces kept detailed records, which survive today on clay tablets. Peasants settled their debts primarily in barley, which everyone needed.

Everyday exchanges were done on improvised credit systems. These were derived from earlier systems of gift giving that have been common in so-called "primitive" societies and are indeed common in all societies. Social and economic relations in simpler societies involve the giving of "gifts," which are actually given in the expectation of future reciprocity. Although it is never stated explicitly, the givers of gifts know that at some future time, when the giver is in need, the recipient will repay the "gift" with some of the same substance or with something else of value. Every human knows intuitively how this kind of gift giving works. These systems of reciprocity were modified in early cities into both formal and informal debt systems that made commerce possible.

Day-to-day purchases from small merchants—a butcher, baker, etc.—would have been handled on interpersonal credit. In a neighborhood, people knew the merchants, the merchants knew their customers, and everyone knew everyone else. Credit and debt at the neighborhood level operated largely on merchants and customers knowing and trusting each other, backed up by laws. Merchants and consumers would have kept records formally or informally, or even in their heads. Peasants repaid their debts at harvest time with barley. Alternatively, a baker might give bread to a blacksmith for several months before the blacksmith repaid with a new knife. Debts to a temple were recorded on clay tablets. The tablets themselves would have circulated as promissory notes. Obviously in such a system there were disagreements and defaults. These would have been handled as they are today, either through the authorities or between individuals. Then as now, merchants could refuse to extend further credit. The important point is that this system worked, awkward though it was, for 2500 years before coins began to circulate. Indeed, something like this continues today, in keeping a tab at the local tavern, in pawnshops, in the informal economy, and in everyday instances of assistance to neighbors and friends.

Indebtedness was, and is, a strategy of *time-shifting* in energy. That is, certain products of energy are accepted today with a promise to repay with the products of future energy. For that matter, money is also a strategy to time-shift energy. No one can eat a gold coin. Its value lies in three areas. Firstly, it can be made into something ornamental, a process that requires energy. Secondly, it can be used at any given moment to purchase useful products of energy, such as tools, or ultimately food. Thirdly, it constitutes a *promise* (like debt) that the products of energy will in the future be available if one surrenders the coin. The gold coin gives one the ability to claim the products of energy at some time in the future. Both debt and money are commitments of future energy.

Early Roman currency gives us a glimpse of how such a system would have evolved into a cash economy once coinage became widely available in a variety of denominations. Until the late fourth century B.C., Roman soldiers were paid with lumps of bronze. They were paid at the end of a campaign and would have accumulated debts until paid. The lumps of bronze had value because they could ultimately be fashioned into implements. In the short term, they were used to settle debts. Toward the end of the fourth century B.C., Roman soldiers began to be paid in standardized bars of bronze, with a design on one or both sides. In the early third century B.C., the bronze was cast into large, heavy coins. These were the beginning of Roman coinage. The value of the bars and coins is that the weights were standardized, although the problem of making change was still significant. Finally, during the Second Punic War (218–201 B.C.), a flexible coinage in bronze, silver, and occasionally gold was established. Only from this time can Rome be said to have had a monetary economy although, as before, many purchases would have still been made using credit and debt.

4.4 Conclusions

Ancient cities were both like and unlike modern ones. Like nearly all cities throughout history and even today, they were dirty, dangerous, and unhealthy. Nevertheless they attracted people for economic and social reasons, as cities still do. Ancient cities relied on the solar energy of the moment to a great degree. The degradation of energy when it is converted from grain to draft animals made the cost of transport high. This limited the size of a city's territory and thus the size of the city itself. In some fundamental ways, ancient and modern cities pursued similar strategies, especially strategies of growth. Two of these strategies are as follows.

Firstly, *find energy subsidies*. Ancient empires typically found energy subsidies through expansion. The Romans, for example, when they conquered new lands, imposed taxes on those lands and the people who lived in them. In this way, the solar energy of the Mediterranean Basin was channeled into Rome, allowing the city to grow to a size and magnificence that would never have been possible with only the solar energy falling on central Italy. As has been common to cities throughout history, ancient cities used water transport as a subsidy wherever they could, a way to circumvent the constraints of land transport. Today we find our subsidies in fossil fuels and nuclear power, with which we support cities vastly larger and more complex than those of the past.

Secondly, *employ time-shifting of energy*. Both debt and money are a commitment of future energy. Both allow one to consume the products of today's energy with a promise to make available the products of future energy or to make available surrogates (tokens such as money) that can be used to purchase those products. Economic differentiation is the essence of cities, and exchange is the basis of urban metabolism. Neither ancient nor modern cities could have existed without debt. Indeed, because cities depend on a way to make transactions, urbanism could never have emerged without debt. Debt, the time-shifting of energy, made cities possible.

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Chapter 5
Economy and Development in Modern Cities

Kent Klitgaard

Abstract This chapter focuses on the roles of energy and strategies for capital accumulation as the primary determinants of urban development. The essay begins with a brief survey of the city in history: ranging from the mercantile trading city, characterized by craft production, to the rise of the industrial city with its large-scale industrial production, to the corporate city based on the service sector, paying special attention to the role of energy surpluses in transforming work processes and expanding economic surpluses. The chapter ends with a discussion of Third World cities, especially megacities, and their role origins in the globalization process, as well as a reflection on the possibility of sustainable cities in the future.

Keywords Economic surplus · Energy · Division of labor · Labor process · Dependency theory · Third World city

5.1 Introduction

This chapter is about how cities grow and decline economically in more recent history. History has shown us that over time, city economies collapsed (See Chap. 4). The roles played by energy, economic surplus, and the development of markets upon the urban process are integral to understanding urban ecology and addressing how or if it's possible to create sustainable cities going forward.

Biophysically speaking cities concentrate energy and, as open systems, regulate its throughput [1]. For a city to grow, it must increase its throughput. If the ability to acquire and distribute energy rises, then a city may expand dramatically and increase its complexity. However, should access to energy suddenly fall, an urban area will see its growth limited and its complexity decline. When seen from a social perspective, cities are enigmatic and contradictory. They are centers of art and culture and have been since the days of antiquity. The most stunning examples of architecture are found in urban areas. Cities house the finest museums, theaters, and universities.

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They are centers of finance, opportunity, and excitement. Yet, at the same time, cities are bastions of inequality. Data compiled for the United States by the Bureau of the Census show that the degree of inequality, as measured by the Gini coefficient,[1] is greater in urban areas than in the nation as a whole [2]. This pattern of urban inequality also characterizes the cities of the Third World. Gini coefficients exceed those found in the United States in the primate cities of most poor nations, for example, Hong Kong, Singapore, and Kuala Lumpur. In much of Asia and Latin America, a greater share of the population lives below the poverty threshold of those regions in urban than in rural areas, even when most of the population is rural [3]. Side by side with the possibility of the acquisition of great wealth lies grinding and seemingly inescapable poverty, overcrowding, failing schools, substandard housing, and the choice between low-wage, dead-end jobs, and recurring unemployment. This dichotomy is not unique to the United States, nor is it a product of modern society alone.

5.2 The City in History

At the beginning of the industrial era when production of commodities supplanted the production of surplus, a technical division of labor in which whole tasks were divided into suboperations became fully developed. Although it was developed upon prior social institutions of the agricultural era its origins can be found in the ancient city as well. Workers themselves developed a social division of labor, but historically they did not turn themselves into lifetime detail workers. This was imposed upon them. It, in turn, shaped the social and physical characteristics, such as spatial patterns, class relations, and architecture of the industrial cities that came later [4]. David Gordon asserts that no particular spatial physical pattern of the built and social environment is predestined for a city. Rather spatial patterns are conditioned by the mode of production, which is a combination of social (class) relations that change very slowly, and the forces of production, or technologies, that change quite rapidly. The clash between the rapidly changing forces and slowly changing relations, along with patterns of accumulation and growth, gives a city its unique character [5]. The Marxist geographer David Harvey puts the matter more succinctly. "In order to understand urban processes, especially in the capitalist era, one must also understand the interacting dynamic of capital accumulation and class struggle. Cities vary over the course of history by how the economic surplus was acquired, the relation of the economic surplus to the energy surplus, and the role of markets in allocating the products and resources that comprise the material basis of the surplus [6]." It is only with the development of market economies after the sixteenth century that an internal dynamic of reinvesting the surplus became imperative.

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[1] The Gini coefficient is a summary statistic of income inequality. The higher the number, the greater the degree of inequality.

5.2.1 The Industrial City

Mercantile cities (circa sixteenth to the late eighteenth centuries) were centers of craft production, and skilled craftworkers limited entry into their crafts, restricted output, and jealously guarded control over technology since medieval days. Urban areas were centers of craft unionizations as much as they were centers of guild power in the medieval period. With the onset of industrialization, fueled primarily by the invention of the steam engine, incipient industrialists who wished to expand to larger-scale production and employ new machine technologies needed to escape the old mercantile cities. In England, the industrial city was built upon coal and the steam engine, as coal became the primary fuel for both textile manufacturing and metallurgy.

By the late 1600s, England had largely denuded its hardwood forests for use as fuel in iron smelting. Early attempts at smelting with coal produced low-quality iron, due to the high sulfur content of available coal and other impurities. After many failed experiments, Abraham Darby finally invented a process for the smelting of high-quality iron using coal as a fuel. William Stanley Jevons asserted that it was improved metallurgy that provided the industrial prowess of England in the nineteenth century [7, 8]. The eventual primacy of coal and the steam engine affected textile manufacturing differently. The problem here was in procuring an adequate labor supply. Rather than displacing wood, coal became a viable substitute for water. Early British textile mills were driven by water power, located mostly in remote rural areas where the waterfalls were located. The largest problem for cotton manufacturers was finding a labor force willing to work the long, arduous, and to former craftworkers, demeaning hours tending water-powered machinery. Rural workers often had the option of farming and were unwilling to provide constant labor. To recruit urban workers, rural water capitalists had to construct entire villages, including amenities, which were very costly. The alternative was to use bound "apprentices" or virtual slaves from the urban poorhouses. The apprentices were bound; the threat of dismissal could not be used. Beatings were largely ineffective, and labor productivity was low. Rather than moving the workers to the power source, steam allowed capitalists to move the power to the workers by the mid-nineteenth century. Second-generation urban workers were more acclimated (or resigned) to factory work than their rural counterparts. Productivity soared, and England became the dominant textile producer in the world [9].

The first industrial cities in the United States also arose along the swift rivers of New England, with water providing the power source for large-scale production and young women from the rural farms providing a less resistant labor force than could be found among the craftworkers of the mercantile cities. However, as coal replaced water and railroads reduced the cost of transportation, the mercantile cities were also transformed into industrial cities. Early power forms that were based on a central source, either water or steam, dictated factory design. Early factories were multistory structures on a small footprint. Each machine needed to be located close to the central power source as to be driven by means of belts and shafts. A great deal of labor time was spent simply moving materials and finished goods up and down the factory's many floors. By 1899, 40% of US manufacturing establishments were factories, and value added in manufacturing doubled between 1859 and 1879, despite the severe depression that began in 1873. By 1895, consumption of coal as a fuel source exceeded that of wood [1].

A difference of opinion exists as to why industrial production returned to the nation's largest urban areas. Mainstream economists and historians stress the concept of agglomeration economies. Factories are located in large cities in order to be close to workers, to intermediate goods and hubs of innovation, and to consumer markets as well as to centralized distribution points of raw materials and fossil fuels (coal). The industrial city of the eighteenth and nineteenth century was a crowded, noisy, polluted, and impoverished place. Lewis Mumford described the industrial city as Coketown, a phrase taken from Charles Dickens' *Hard Times*. "Industrialism, the main creative force of the nineteenth century, produced the most degraded urban environment the world had yet seen; for even the quarters of the ruling classes were befouled and overcrowded" [10, p. 447]. The congestion and diseconomies of scale increased costs and impeded the exchange of intermediate goods. The increase in urban population, in excess of the social and physical ability to support this population, especially in Third World cities, has come to be known as "overurbanization." In spite of these problems with agglomeration, urban concentration of factories increased, nonetheless. Gordon attributes this to issues of control [5]. Urban concentration allowed industrialists greater control over labor. The mercantile city had been plagued with resistance to the increased pace of production and technological change. Artisans and skilled workers fought the imposition of the division of labor as a threat to their traditional control over design, as well as the pace and quality of work. Achieving labor discipline was needed in order to make economies of scale cost-effective. Urban areas offered two main benefits. The labor process needed to be transformed, not merely expanded. Skilled craftworkers needed to give up power to a more docile workforce who would serve as semiskilled operatives. In the words of the Social Structure of Accumulation School, the labor force needed to be homogenized. The large number of workers, especially immigrants, served this purpose only in large cities. Moreover, the middle and commercial classes (shopkeepers) were more hostile toward the working classes (especially immigrants) in large cities than in those of middling size. There were, therefore, fewer strikes and lockouts in larger urban areas, and those that occurred did not last as long as those in smaller cities. Large urban areas contained isolated wards of working-class people and immigrants. They did not mingle as did those in the preindustrial city or as they did in smaller cities. Consequently, one was more likely to find preindustrial attitudes of equality in smaller cities than in larger ones [5].

Industrial cities shared four characteristics independently of their particular spatial location. They all had huge factories concentrated in the downtown area, at a scale greater than anything seen in prior eras. Segregated working class districts emerged adjacent to the factory district. Little attention was paid to light and ventilation, often with buildings backed up one against the other, for example, the tenements of New York's Lower East Side. Those with enough wealth or income escaped to the suburbs. The mercantile city was ringed with the poor. In the industrial city, the poor and dependent wage workers occupied segregated working-class wards, while the wealthy ringed the city. This phenomenon was described by authors as varied as Frederic Engels, in his *The Condition of the Working Class in England in* 1844 [11], and Ernest Burgess, Chicago-school theorist of urban studies in 1924 [12]. In the mid-nineteenth century, the high cost of keeping a horse and carriage kept all but the very wealthy from escaping the city's noise, overcrowding, and pollution. The subsequent development of the electrified streetcar, and eventually the automobile, opened suburban living to a broader segment of the middle class. Finally, the interaction of the upper and middle classes with the city occurred primarily in downtown shopping districts [5]. Specialty shops would move to the suburbs only after the age of the automobile [1].

Throughout the late 1800s, conditions began to change in the industrial city. Labor control began to be more problematic after the depression of the 1870s, and the large-scale immigration from Southern and Eastern Europe blossomed. There was also a building boom in the 1890s. Immigration kept down wages, and the increased housing and building supply reduced the growth of rents. However, urban areas began to be hotbeds of union activity. Factories would begin to locate, once again, on the outskirts of large urban areas. This could not have happened in the absence of increased fossil fuel consumption and the technical innovation that it made possible. The urban suburbs of the late nineteenth and early twentieth centuries depended upon electricity for the motive force of machines and for transportation.

5.2.2 Transition from the Industrial to the Corporate City

Social and biophysical forces shaped the transition from the industrial city to the corporate city. In order for the modern city, built on services, mass consumption, suburban living, and production, to evolve, fundamental changes in the flow of energy through a city had to occur. It is my contention that social explanations of the rise and fall of the corporate city are themselves insufficient. Certainly issues of power through merger and reorganization of the labor process are important and underappreciated. However, social changes in spatial relocation, the transformation of the labor process, and the expansion of consumer markets depended also upon fundamental changes in the way we generate and use energy. The industrial city was enabled as much by fossil fuels as by any purely organizational change. Louis Mumford showed early insights as to the interrelated importance of the social and biophysical forces that shaped the city. "The generating agents of the new city were the mine, the factory, and the railroad" [10, p. 446]. Although socially the industrial city depended upon organizational and political changes such as the eliminations of craftwork and controlling guilds, the creation of a state of dependent and permanent insecurity for the working classes, and the creation of a labor market to accompany a market for goods and services, economically the city depended upon biophysical developments. "Its economic foundations were the exploitation of the coal mine, the vastly increased production of iron, and the use of a steady, reliable—if highly inefficient—source of mechanical power: the steam engine" [10]. There is one further urban evolution that must be explained before the conclusion of the "City in History"—the modern corporate city.

5.2.3 The Corporate City

In the late 1890s, manufacturing began to relocate to the outskirts of town. Between 1899 and 1907, central city employment increased modestly (40.8%), while manufacturing in the suburban rings nearly doubled. Plants removed from the central city had lower rates of unionization and paid lower rents, thus increasing profits to manufacturers and to those who owned shares on the newly emerging, and highly speculative, stock exchanges, which had arisen with the financing of the railroads. Gordon [5] explains the timing of the industrial exodus from cities that resulted from the merger wave of 1898–1903. Only large corporations could afford the capital investment, especially on the heels of the depression of 1893–1897. Workers followed their employers to the suburbs. The old downtown shopping districts were transformed into broader central business districts that included not only retail sales but also financial districts and the location of corporate headquarters performing command and control functions. The former working-class wards were transformed into urban ghettos, leaving consistent patterns in many different cities across the industrial world of gleaming new skyscrapers surrounded by dilapidating quarters of recent immigrants across the old industrial cities. As the nation "deindustrialized" in the second half of the twentieth century, this pattern remained. Old industrial cities, primarily in the east, had a great deal of physical capital that had been left to degrade. The transformation from the industrial city to the corporate city of today was not an easy process. It took at least five decades of the forcible removal of the poor and the replacement of substandard but "affordable" housing by new structures of commerce, which exacerbated the problems of homelessness. This process of gentrification is not entirely complete in the older cities of the Northeastern United States. The story is different in the west and the southwest, where new cities were constructed in the twentieth century and no legacy industrial cities existed. They were built largely without city centers, lacked inner city industrial districts, and were constructed for the automobile. No large-scale destruction of nineteenth century factories had to occur [5, 13]. These historical and geographical patterns have great effect on energy consumption and the future of cities.

Both assembly line mass production and mass consumption were built on a backbone of electricity. The ability of middle classes to escape the decaying city and live a more idyllic life in the suburbs depended upon cheap transportation, and cheap transportation depended upon cheap energy. The next section will chronicle the development of electrical power, which revolutionized both production and consumption, the rise of the gasoline powered automobile, and some of the environmental ramifications of these changes in energy throughput. The modern corporation, and the modern corporate city, were built upon the unification of low-cost mass production and mass marketing [14]. Few technologies impacted production and consumption as did electricity.

Its general use in production fundamentally altered the labor process and enabled the organizational changes often known as “Taylorism” or “Fordism.” Taylorism entailed the separation of the brain work from the manual work or more precisely *conception* (of, e.g., ideas) from *execution* (of, e.g., products). In addition, millennia of craft knowledge were to be appropriated by management and given to workers who were to follow explicit instructions. Taylor largely augmented the process of the division of labor with a greater degree of detail and management control. Fordism combined large-scale, assembly line, production with the mass marketing of product plus wages sufficient for workers to make major purchases (such as automobiles) without access to credit [4]. Without electricity the advances in efficiency that reduced cost and homogenized labor would scarcely have been possible. Moreover, the coming of electrification helped create the culture of mass consumption. Early pioneers of electrification such as Chicago’s Samuel Insull based their business strategies on low-cost production and an expanding market. The two were closely interrelated. Electricity first came to urban areas due to the concentration of customers. Only later would rural electrification projects command the political and economic stage. The earliest suburbs of cities located in the Northeastern United States depended upon electrified railways to make suburban living affordable to the middle classes. Life in the post-World War II suburbs was highly dependent upon electricity. Most of the products we associate with modern society, from consumer goods such as refrigeration, electronic media, air conditioning, and computers, require a steady and reliable source of electrical power. In addition, the machines with which our consumer goods have been built, and the transportation systems with which we move them, depend on electricity. During a power outage, you could not even fill your car with gasoline.

5.3 Third World Cities

Cities in poor countries share many of the problems and dynamics of cities in wealthy nations such as the United States. However, given their status as a metropolis of poor nations with subordinate status in the world economy, cities in poor, or less developed, nations have a set of unique problems and challenges. Such cities are often referred to as Third World cities. The term appeared in the 1950s to describe nations that were neither aligned with the capitalist west (the First World) nor the socialist east (the Second World). The term is largely synonymous with the poor nations of “the Global South” contrasted with the rich nations of “the North.” The distinction between the affluent North and impoverished South was first made in the Brandt Report of 1981, a United Nations document issued by former German Chancellor Willy Brandt. Third World cities exhibit a tremendous degree of diversity. Some, such as Cairo, Egypt, are ancient, while others such as Harare, Zimbabwe, or Nairobi, Kenya, are modern creations. Some retain their mercantile roots, others are centers of industrial production, while still others are modern, gleaming outposts of global finance, surrounded by squalid slums. The factor that unites these cities, despite their differences, is their linkages to the global economy and the structure of global capitalism [3]. Sociologist David A. Smith asserts that analyses of Third World cities in a global context require a theoretical framework and posits that *dependency* and its later evolution, *world systems theory,* are the best, if not the only, viable theoretical mechanisms by which to analyze their growth and development.

Dependency theory began with the work of Paul Baran in the late 1950s. In *The Political Economy of Growth* [15], he argued that poor nations would remain poor because the economic surplus that would allow for investment and increased consumption is systematically drained from former colonies by imperial powers in a process that did not end with formal decolonization. He called this process the development of underdevelopment [16]. Poor countries are often resource rich. However, the benefits do not accrue to the poor nation because of a global imperialist system that has characterized the Global South for at least 400 years. Following Baran's lead, Andre Gunder Frank formulated dependency theory. In dependent development the economic surplus flows from satellite to metropolis. The metropolis could be both the rich nations where the surplus ultimately flows and the Third World city where the economic surplus, often agricultural or mineral, flows on its way to the nations of the global North. Third World elites are more closely tied with international capitalists than with their own populations. Gunder Frank derisively termed them the "lumpenbourgeoisie." (Lumpen is German for "rags.") In this way city growth is altered to fit the needs of the overall global economy. The city is the nerve center of exploitation in satellite countries [17].

Dependency theory has evolved into what has come to be known as world systems theory. The classification of nations is expanded whereby the former metropolis becomes the core, and the satellites are most commonly known as the periphery. In between are the middle-income nations of the semi-periphery, for example, Argentina, Brazil, Mexico, South Africa, and South Korea. A consistent analytical focus characterizes world systems theory. The crucial insight is that the process of urbanization is best understood as part of a process of the expansion of the world economy. David A. Smith contends that this is the only way in which urbanization can be understood. Urban analysis should focus upon (1) the historical context of urban development and the world economy, (2) the politics of the state, (3) intracity inequality and the role of the informal sector, and (4) overurbanization.

Urban inequality has a great deal to do with the dynamics of overall development, and much inequality can be traced to the functioning of labor markets and labor processes. The fundamental problem is that urban population has been growing faster than the ability of urban areas to absorb the surplus rural population. A case in point is Lagos, Nigeria. The growing surplus population results in a downward pressure on wages and the creation of a large informal sector in peripheral and semi-peripheral societies. Drakakis-Smith [3] estimates that 80% of the Indian labor force works in the informal sector. Women and children tend to occupy the lowest rungs of the informal sector characterized by low wages, irregular and casual employment, small enterprises, and few benefits. While many mainstream commentators connect the rise of the informal sector to the problem of overurbanization, where the enormous influx of population creates inefficiencies in production and the provision of services, international political economists such as Smith and Drakakis-Smith see the rise of the informal sector as far from dysfunctional in dependent peripheral societies. By keeping production costs low and taking on activities that would otherwise be unprofitable for multinational corporations (such as recycling metals and electronics), the informal sector provides a very efficient mechanism for transferring economic surplus from peripheral and semi-peripheral societies to the core economies [3, 17]. The role of the informal economy is not so different from that of benthic macroinvertebrates in a stream ecosystem that consume detritus like leaf litter and hence recycle nutrients back through the system. This is why we can study a city as a socio-ecological system because the functions are the same in human and “natural” or “wild” systems.

The poor in the rapidly growing Third World cities are most likely to suffer from environmental degradation, particularly in the form of wide-ranging pollution, land degradation, hazardous living, and poor working conditions. Environmental problems are particularly manifest as household health problems such as cholera, tuberculosis, and typhoid, attributable largely to lack of access to pure water and substandard housing. Indeed, housing is perhaps the most visible symbol of inequality (much as in the United States). Fifty to seventy-five percent of housing is squatter housing in West African cities from Monrovia (50%) to Lomé and Ibadan (75%). Unlike the United States that developed an initiative of slum clearance and the debt-based expansion of home ownership, many Third World cities have no such program. Many are constrained by the terms of structural adjustment programs (see Box 5.2), and many states are lax to raise taxes on foreign investors to pay for health and housing under fear of creating a bad business climate. It should be noted that much industrial pollution in Third World cities is created by small enterprises, especially in food processing, tanning, textile production, and electroplating [3]. Advocates of sustainability by means of entrepreneurship often ignore the adverse activity of marginal enterprises in the informal sector.

Box 5.1 Structural Adjustment Systems

Structural adjustment programs (SAPs) were initiated in the late 1970s and early 1980s by the World Bank and the International Monetary Fund in response to the changing conditions of the 1970s, including oil crises, a debt crisis, an international run on the dollar, stagflation, and recurring depressions in poor countries. The policies were aimed primarily at the macroeconomic problems of debt and fiscal imbalance. To qualify for future loans, debtor countries had to reduce government spending, especially social spending on education and health care, and raise taxes, in order to make their balance sheets attractive to international investors. Many development scholars see SAPs as a method of increasing and perpetuating Third World dependency.

Sassen [18] attributes the rise of inequality to the rise of global cities. Global cities fulfill the command and control functions of the corporate city on a world scale, and the process is aided by the advancement of information technology. Global cities are the locations where producer services (management information systems, law, accounting) and financial innovation reside. Despite the high costs of agglomeration and overurbanization, synergies among and between these high-income professionals make the city an attractive place for the information sharing needed to pursue innovation. However, global cities as hubs of innovations also create myriad low-wage jobs such as janitors, nannies, street cleaners, casual service providers, and very few jobs in the middle as the industrial bases have been lost. Global cities such as Singapore or Hong Kong are more likely to look like New York or London than smaller cities in their own regions and indeed thrive on and perpetuate the transfer of economic surplus from peripheral areas [18].

5.4 The Rise of Megacities

A new phenomenon appeared at the end of the twentieth century and will certainly come to be one of the most dominant urban features as the twenty-first-century progresses: the rise of megacities. Megacities are defined as urban areas with an excess of ten million inhabitants. In 1950, there were only two: Tokyo and New York. By 1975, Mexico City was added to the megacity mix. In 2007, there were 19 such megacities, including Tokyo as a hypercity, with a population in excess of 20 million. The United Nations projects that by 2025, there will be 27 megacities, 14 of them in Asia, including eight hypercities [19]. While attention is often focused on megacities, three quarters of urban growth have occurred in second cities. Today there are 400 cities with populations in excess of one million, as cities have absorbed almost two-thirds of population growth since the 1950s. The world became primarily urban in 2008, and the present urban population is expected to grow, while the rural population will peak in 2020 and decline thereafter [20] (see Chap. 1 for UN projections for 2100).

What will be the character of twenty-first-century megacities, especially those in less developed countries? Just as cities in the past, present-day megacities can have gleaming central business districts, cultural diversity, and many opportunities. On the other hand, they can be bastions of poverty, unemployment, and disease. One example of a functioning megacity is Singapore. A former British trading port at the base of the Malay Peninsula, Singapore's population has grown at an average of 2.2% per year since independence in 1960, doubling every 36 years. The growth in population has been matched by an increase in well-being for many of its citizens. Singapore is a wealthy country with the world's third highest per capita income of $60,688, according to the World Bank, and the degree of inequality, as measured by the Gini coefficient (0.473), is just slightly in excess of the inequality of the United States (0.450). Singapore provides services and technology for most of Southeast Asia and serves as one of its financial hubs.

Box 5.2 The Gini Coefficient

The Gini coefficient, named after Italian economist Corrado Gini, is a summary statistic of income inequality. To construct this index, one first divides the income distribution into five equal groups of 20% each (quintiles). The index then poses a theoretical "line of perfect equality," whereby each quintile receives 20% of the nation's income. The next step is to plot the extant income distribution (the Lorenz Curve) and compare the area between the curves. The Gini coefficient is computed as the ratio of the area beneath the line of perfect equality to the area beneath the Lorenz Curve or the ratio of A/A + B. The coefficient varies between 0 and 1. The higher the Gini coefficient, the greater the degree of inequality (Fig. 5.1).

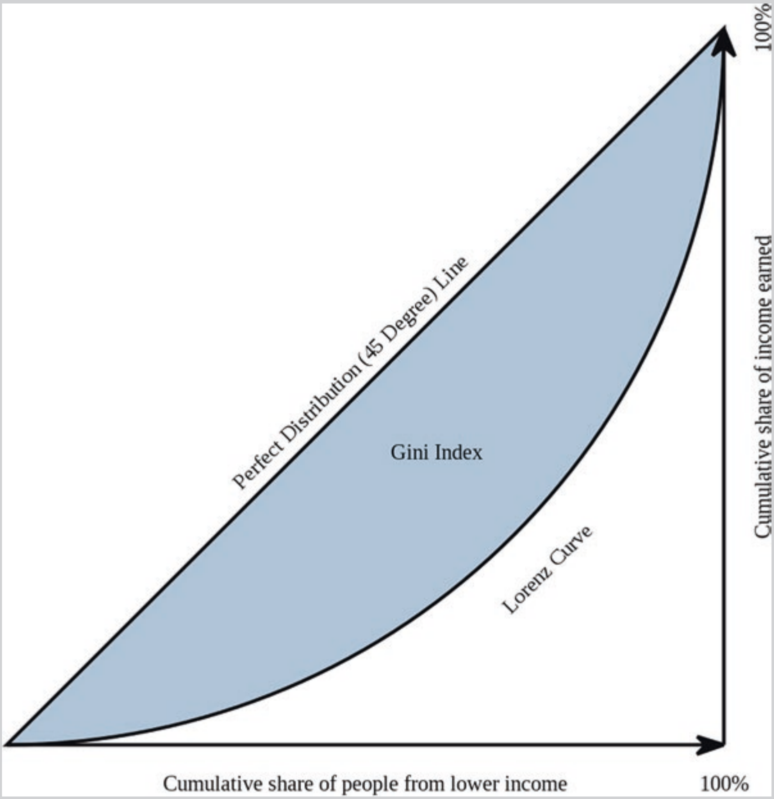

Fig. 5.1 The Gini coefficient (Source: Reidpath, Economics_Gini_coefficient2.svg at https://commons.wikimedia.org/w/index.php?curid=7114030, revision of the original file on WikiMedia Commons (http://en.wikipedia.org/wiki/File:Economics_Gini_coefficient.svg) by BenFranzDale at en.wikipedia, vector drawing of original:File:Economics Gini coefficient.png by Bluemoose, License: Public Domain

Singapore attracts foreign investment in pharmaceutical and biotechnology and is the world's busiest port. It has a democratically elected government and ranks second on the Heritage Foundation's Index of Economic Freedom list [21]. This list attempts to measure the neoliberal idea of free markets by quantifying the rule of law (primarily property rights), limited government, regulatory efficiency, and open markets. The United States is tenth on the list, while North Korea and Cuba bring up the bottom. (It would be hard to imagine two societies who have responded more differently to food crises at the end of the first half of the age of oil than North Korea and Cuba, but the Heritage Foundation ranks them together, nonetheless [21]. At the opposite end of urban functionality lies Lagos Nigeria. Lagos is the commercial center of West African finance, especially as regards the oil industry, and is the leading port in Africa. It is also a center of education with Lagos State University ranking among the finest in Africa and is home to a vibrant music scene. Unfortunately, the institutional structure and infrastructure of Lagos have been utterly overwhelmed by an influx of rural migrants too large to be accommodated by the formal structures of the economy. Teeming slums ring the city, much as they did in the mercantile city, and the migrants have few prospects for a prosperous future. In the words of African Political Scientist Tukumbi Lumumba-Kasongo, "Lagos does not work." In order to understand why Lagos does not work, you must also understand its political economy" (Tukumbi Lumumba-Kasongo, *personal communication*).

Understanding the political economy of Lagos entails developing an analysis based on class processes and historical interaction with the rich and in this case colonizing nations of the world. In the era of the corporate city, urbanization must be seen as a structural transformation of an urban-rural continuum. The countryside is being urbanized as migrants flow to the cities. Former rural towns themselves become cities. The question remains why do migrants leave the countryside for the cities? The mainstream explanation is that they migrate in search of greater monetary opportunities. Even low urban wages exceed what can be found in rural areas. The process of the individual acquisition of wealth is as important as an explanatory variable of the political economy in Lagos as it is in Singapore. Cities must grow economically and geographically to absorb the rural surplus population [22]. A political economy approach looks more to the structural dynamics occurring in the countryside. Urban slums have their origin in rural areas. Biophysically the application of fossil fuels to agriculture (mechanization, pest control, weed control, etc.) has rendered much of the rural population redundant. In addition, the "reforms" of the neoliberal area, such as privatization, the removal of capital and export controls, the end of food subsidies, and a general decline in the public sector have opened rural areas to competition with transnational agribusiness firms. Traditional rural populations simply cannot compete on price terms in the international market. Displaced from their culture and land, migrants stream to urban areas in such overwhelming numbers that the cities cannot possibly accommodate them. This is the process known as overurbanization.

Even if the process of creating fewer jobs is an inherent part of the globalized economic system, the situation in many Third World nations was made much worse in the form of neoliberal policies such as structural adjustment programs in the

1980s. Designed to implement the neoliberal dream of free and unimpeded movement of capital around the globe, the repayment of loans from multinational banks and multilateral lending agencies was given first priority. The consequent austerity policies reduced internal demand, exacerbated capital flight, and led to only marginal, at best, increases in exports, with increases in prices, reduced real wages, and declines in formal employment. In Nigeria, extreme poverty increased from 28% in 1980 to 66% in 1986, and per capital GDP fell below the level found at independence in 1960. Urban inequality also exploded. In Buenos Aires the ratio of the income earned by the top decile relative to the lowest decile (the P-90/P-10 ratio) increased from 10:1 to 23:1 from 1984 to 1989. In Lima, Peru, the poverty rate increased from 17% in 1985 to 44% in 1990 [20].

The dilemma is one of the failed growth economies: an economy that must grow to provide employment and opportunities but that simply cannot grow within the context of a stagnant (slowly growing) economy in the context of globalized monopoly finance capitalism. Unable to find steady and well-paid employment, migrants flock into the informal sector where they join former civil servants and displaced professionals rendered unemployed by the SAPs and decline in domestic demand that resulted from IMF-imposed austerity measures. Cities have simply been the dumping ground for the surplus population. Overall, informal sector workers account for 40% of the economically active population in less developed countries, 57% in Latin America, and 80% of new jobs as of 2004. Yet even informal employment, with its uncertain income, cannot absorb fully the increase of one million babies and migrants per week. For example, the informal sector in Zimbabwe creates approximately 10,000 jobs per year, yet the nation's cities are forced to absorb some 300,000 additional bodies per year [20]. The health and environmental consequences of urban growth have no immediate answer within our present institutional structure.

5.5 The City of the Future

In the era of climate change, peak oil, peak debt, falling wages, and a widening gap in income distribution, present urban American systems, such as housing, transportation, education, and governance, will no longer be viable. The present urban configuration was built upon cheap energy. As the era of cheap energy passes, cities must restructure themselves in order to remain viable in the second half of the age of oil. The sooner we begin the process, the better off we will be. The problem is not simply "running out of energy." As conventional oil peaks on a world scale, alternatives certainly will be forthcoming. However, there is no guarantee, nor even indication, that the alternatives will have an equally high energy return on investment (EROI). If not, the alternatives are likely to be more expensive, less available, and most likely dirtier in terms of carbon emissions. Technological change in the energy industries has not taken the form of finding new sources of hydrocarbons but in developing methods of extracting previously discovered but unprofitable sources.

The combination of horizontal drilling and hydraulic fracturing and the mining of Canadian oil sands are flooding the market, as of 2013, with new sources. Up to 60% of new oil discoveries are in deep water. The fundamental energy problem facing cities, nations, and the world is, and will be in the future, the problem of falling EROI [23]. As more energy must be used to acquire additional sources of energy, myriad economic problems will occur. Higher input costs lead to higher energy prices for the consumer, although the process is not a smooth one. Higher energy prices choke off demand, helping precipitate a recession. The recession reduces energy prices, helping to restore prosperity. The global peak of oil looks more like an "undulating plateau," and the uncertainty adversely impacts the financing of future high cost energy sources. Fossil fuels have brought those lucky enough to acquire cheap energy a respite from back-breaking labor and have allowed the expansion of our infrastructure and our educational and health-care systems. We seem to be faced with a choice, find new sources of cheap energy, or learn to live with less. It is no wonder why the vast majority of people keep seeking new energy, from methane hydrates to hydrogen to shale gas. Living with less and returning to longer days of physical labor is not personally appealing, and living with less is basically incompatible with an economic system that must grow in order to provide employment and opportunity. Moreover, new sources of energy are not a panacea. The hydrocarbons already discovered would raise the threshold of atmospheric carbon dioxide above the 450 parts per million threshold that the world agreed in 2009 at the Copenhagen Climate Summit would bring about irreversible climate change. Methane hydrates are as likely to be a powerful greenhouse gas as they are an easily and cheaply exploitable energy source [24].

What will take the place of cheap fossil fuel? Social critics such as James Howard Kunstler [25] argue that the first cities to go will be the desert boomtowns of the American Southwest. These cities, soon to be desperately short of water and air conditioning, and with no central core to make public transit viable, will simply have to be abandoned. Long before their budgets are broken by the electricity costs of pumping water as well as providing air conditioning on a warming and drying planet, the construction and finance, insurance and real estate industries that provide the bulk of employment will have been compromised beyond repair in a nongrowing economy.

Kunstler and Austin Troy believe the future lies with smaller compact cities by means of infill development and the provision of appealing public closed and open spaces. Bicycling, walking, and transit will account for the bulk of transportation. Troy [26] cites the Scandinavian cities of Copenhagen and Stockholm as examples to learn from. Kunstler points to the necessity of mixed cities where commerce and residence coincide with apartments above street-level enterprises, much like European cities, which were built long before the fossil-fuel era. The changes will have to be structural, not technological. As he says, "No combination of alternative energies can possibly support Disney World, Las Vegas and the interstate highway system."

Michael Stone and his colleagues point to income cost contradiction as the fundamental problem. Because of the high costs of construction, houses will remain expensive. Yet to raise incomes enough for housing to be affordable to the majority of workers would collapse the neoliberal vision of the labor market. To reduce the price of housing would collapse the housing and finance industries as well as destroy the main source of wealth, housing equity, for the majority of Americans. They recommend a combination of social housing strategies: well-constructed and maintained public housing without the social stigma; co-housing; social housing where structures may be owned but the land is held in trust [27].

5.6 Conclusions

These problems will be even greater in the burgeoning Third World cities. One thing that dependency and world systems theory teach us is that one cannot make the necessary changes to create livable, walkable cities with reliable public transportation; regional production of food, goods, and materials; and local organic agriculture without also changing the institutional structure of dependent development and global monopoly finance capitalism. There is simply no mechanism by which the clock can be turned back to a point where small-scale, energy-efficient, regional small business can replace large-scale, globally concentrated, financially dominated multinational enterprises. Perhaps, as Rubin [28] argues, the coming of global peak oil will force these changes despite our most desperate political actions. But resource deprivation and the stagnation of economic growth do not automatically imply a trend toward equality and the provision of basic human rights such as health, shelter, access to pure water, employment, and education to the many urban citizens of the north and south alike. The struggle to create sustainable cities is the struggle to change the current international institutional order. I do not know exactly what this will look like at this point in history, although I hope for the low-consumption, walkable, and livable city envisioned by Kunstler. I do know what the future cannot look like. It can be neither Soviet- style drab cities surrounded by heavy industry nor can it be the sprawling suburbs and gleaming central business districts surrounded by dilapidated housing and desperate people. The question is how do we get from where we are now to where we want to be? At this point I do not know but certainly believe cities will be a crucial part of producing and consuming in the future.

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Part III

Urban Ecological Systems: Structure, Function, Controls, and Effects on Social-Ecological Metabolism

Chapter 6
The Urban Hydrological System

Ning Sun, Karin E. Limburg, and Bongghi Hong

Abstract This chapter treats the urban system's intersection with the water cycle. The water cycle will be explained, and the city's local and regional effects will be examined. These will include water routing to and from humans, water consumption (drinking and other uses) and sewering systems; runoff interactions, how impervious surface affects runoff from precipitation events, including the storm hydrograph, particle transport from streets, and combined storm overflows; atmospheric interactions, how the urban heat island and air pollution affect evapotranspiration and precipitation; urban recipient waters, streams, lakes, rivers, estuaries, and wetlands; the role of green infrastructure in the hydrological cycle; and the potential impacts of climate change

Keywords Urban hydrological system · Urban water cycle · Urban stream metabolism · Green infrastructure · Urbanization · Climate change

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6.1 Introduction

The primary purpose of this chapter is to establish understanding of how urban systems intersect with the water cycle, also called the hydrological cycle. We will begin with an overview of how the cycle functions naturally and how the components or the physical processes that make up the water cycle interact with each other to drive the cycle. Then we will examine the principal factors that influence water movement and distributions in the context of the urban environment, followed by a review of the implications of climate change as well as anthropogenic changes such as development (e.g., urbanization) on water quantity (availability) and quality in an urban hydrological system. Having this basic knowledge is vital to creating more sustainable urban living environments where people need access to fresh water, flooding can be detrimental to the urban economy and human health, and ecosystem integrity of downstream waterways must be maintained.

6.2 The Hydrological Cycle

6.2.1 Definition

The hydrologic cycle can be described as the continuous circulation of the Earth's water through the hydrosphere, atmosphere, lithosphere, and biosphere. It is a dynamic and integrated system of stocks and flows driven by a multiplicity of interacting processes including precipitation, infiltration and percolation, evapotranspiration, snow accumulation and melt, canopy interception, sublimation/condensation, etc. [1–3]. To comprehend this system as a whole, we have to understand not only the components that comprise the system but also the dynamic interactions and feedback mechanisms between the processes.

The hydrologic cycle has no starting point. However, let us say that the cycle starts from sun-powered *evaporation* from the ocean (Fig. 6.1). Liquid water changes into water vapor due to heat energy produced by solar radiation and forms clouds in the atmosphere through the process of *condensation*. With suitable temperature and atmospheric pressure, the vapor becomes liquid, and *precipitation* occurs in the form of rain, snow, hail, etc. With liquid precipitation a portion returns to the ocean where it evaporates back to the atmosphere. Initially, however, a portion of rainwater may be intercepted (*interception*) by vegetation, buildings, and other objects from which the rainwater may be either evaporated back to the air or move down from these surfaces to the ground surface. Once the water reaches the ground surface, one of following three processes occurs: (1) Water is stored temporarily in natural depressions, e.g., pits and trenches, and will be lost largely by evaporation. (2) Water soaks into the soil, i.e., *infiltration*. Some of the infiltrated water is lost via soil evaporation and/or is transpired by plants. Combined, these processes are called *evapotranspiration*. The remaining water continuously moves downward

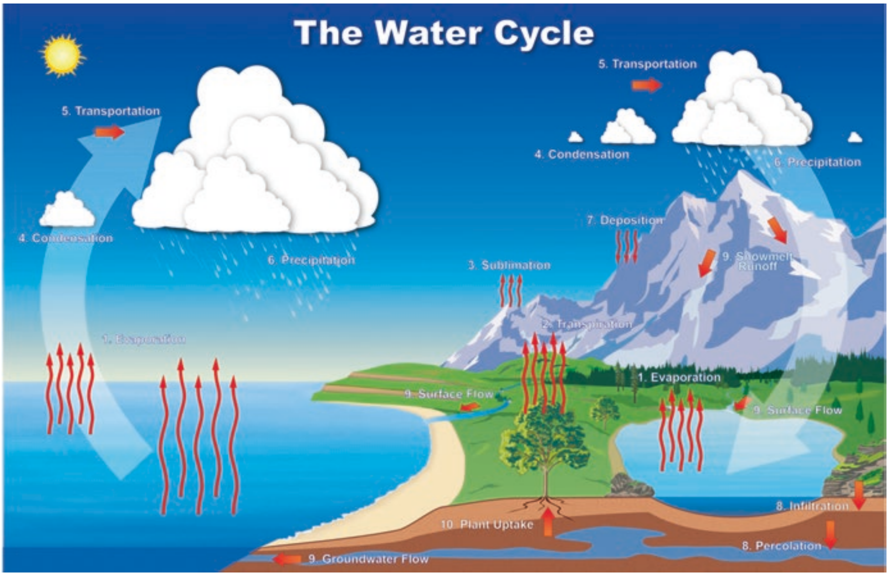


Fig. 6.1 The hydrologic cycle. Graphic courtesy of the National Oceanic and Atmospheric Administration National Weather Service, released into the Public Domain. https://www.noaa.gov/resource-collections/water-cycle

through the soil profile following infiltration in a process called *percolation* and recharges the groundwater that will eventually discharge into streams and return to the ocean (*groundwater flow*) where the cycle begins again. (3) When the water holding capacity of soil is exceeded, rainwater may flow over the surface (*surface runoff*) and will eventually reach the ocean. When precipitation falls as snow, much of it, especially in high-altitude mountain regions, is temporarily stored as snowpack (*snow accumulation*) although some water returns to the atmosphere through the process of *sublimation*, which is the process of snow changing into water vapor without melting first. Long-term storage of water can occur in glaciers and ice caps. The hydrologic processes described above for liquid precipitation begin as snow starts to melt (*snowmelt*).

6.2.2 Physical Factors that Influence the Hydrological Cycle

Hydrologic processes are highly variable both spatially and temporally as a result of complex interactions between climate, terrain, soil, and vegetation. The global hydrologic cycle, however, is less variable compared to that that occurs at smaller geographic scales (such as regionally or even in a small watershed) because variations in some regions can be counteracted by opposite variations elsewhere. Here we focus on the physical control factors that govern regional to local hydrologic cycles. The physical factors can be grouped into two categories: (1) *meteorological factors* including precipitation characteristics, air temperature, solar radiation, humidity, wind speed, etc. and (2) *physiographic factors* such as topographic characteristics, geological factors that have created the hydrological characteristics of surface and subsurface soil layers, and land use and land cover.

6.2.2.1 Meteorological Factors

At a given geographical location, precipitation, which determines the water availability circulating in the water cycle, is one of the primary drivers of the hydrologic cycle over time and space [2, 4, 5]. Under the *rain-only* situation, the rainfall characteristics of volume, timing, intensity, and duration have direct impacts on the water available for surface, subsurface and groundwater flow, as well as soil moisture. In the case of small rainfall events, before runoff begins, the majority of water is lost to what is called the *initial abstraction*, which includes water retained in surface depressions, water taken up by vegetation, soil evaporation, infiltration, percolation, etc. No runoff will occur if the remaining rainwater does not exceed soil capacity. (“Lost” is used by hydrologists to account for what happens to the quantity of precipitation once it falls on the Earth, as in a mathematical equation.) Storm events of short duration and high intensity tend to produce higher peaks in flow volume, while long-duration moderately large rainfall events often generate less runoff as a large proportion of rainwater is lost to soil. In high-latitude mountainous regions, where snow represents a considerable proportion of precipitation, the hydrologic cycle is affected in many ways by winter meteorological conditions. The hydrological processes in snow-dominated or transient rain-snow zones at intermediate elevations are often much more complex than those of low-altitude rain-dominated zones [6]. The magnitude and timing of snow accumulation and melt can vary considerably from point to point as evidenced by the long-term point observations of *snow water equivalent* (SWE) from the Natural Resources Conservation Service Snow Telemetry stations (NRCS SNOTEL) across the mountain regions of the western United States [7, 8]. The marked spatial heterogeneity can be attributed largely to the complex interplay between local meteorology (e.g., precipitation, air temperature, radiation, wind speed, and direction), terrain (slope and orientation), and forest canopy and structure [9–11].

Another hydrological process that can be very responsive to meteorological conditions is evapotranspiration. Soil evaporation and plant evapotranspiration account for a great proportion of water loss from plants and soils especially in arid areas. In humid regions, the evapotranspiration rate is generally slower than in arid regions because the water vapor content in the atmosphere tends to be close to saturation and less water is able to evaporate into the air. Evapotranspiration is also noticeably reduced during cold seasons when plant growth and metabolism are generally diminished [2, 3]. When we discuss the evapotranspiration process in winter conditions, we must take into account the additional reduction in evaporation as a result of frozen soil and the lack of leaves on deciduous plants. When soil temperature drops below 0° C, water in the soil may freeze and thus dramatically hinder water infiltration into the soil [12].

6.2.2.2 Physiographic Factors

There are a number of factors we call physiographic that play a key role in land surface hydrological processes principally that of runoff. We emphasize runoff of surface water as this is the part of the hydrological cycle that can be most detrimental to waterways, both urban and rural. Flooding, erosion, stream sedimentation, and pollution of waterways are all related to runoff. Topographic (landform) features that influence runoff are *altitude/elevation*, *slope angle*, and solar *orientation or aspect (N*, *S*, *E*, *W).* These, along with land cover characteristics such as type of vegetation, amount of vegetation, amount of paving, etc., are the physical features of an area. Elevation and slope play significant roles in determining the surface and subsurface runoff direction, travel time, and volume. The upslope contributing area determines how much precipitation is captured and potentially drains to any point in a watershed, which can be thought of as the outlet of the watershed [13–15]. Slope orientation has a direct impact on the amount of sunlight or incident radiation reaching the surface and thus is very important to the distribution of soil moisture and vegetation [13–16]. Land use and land cover characteristics play a critical role in the hydrologic cycle as well. Natural vegetated cover and impervious land cover produce quite different effects. In densely forested environments, canopy cover significantly alters the surface mass and energy balance through evapotranspiration, canopy shading, and canopy interception, which control the availability and seasonality of river flow especially in snow-fed rivers [10, 11]. Deep-rooted trees and plants can improve soil structure and increase soil infiltration capability, thus reducing runoff potential [17]. Vegetation cover also has been found effective in trapping pollutants borne by runoff, acting as a natural filter protecting groundwater and surface waters from contamination [18–20].

Another physiographic factor in hydrology that influences the hydrological cycle is geology. Surface and subsurface soils are the product of the rocks that were laid down long ago in an area and acted upon by weather over centuries. Clay soils versus sandy soils, for instance, have quite different properties that affect how much precipitation is absorbed versus how much becomes surface runoff. Geology thus accounts for the hydrologic properties of soils, such as hydraulic conductivity, permeability, and the hydraulic gradient [15, 16]. These properties together determine the velocity at which groundwater moves. (*Saturated*) *hydraulic conductivity* is a measure of the water-transmitting capability of an aquifer. A high hydraulic conductivity value indicates that an aquifer can readily transmit water through a saturated zone. In general, coarse-grained sands and gravels have high hydraulic conductivity values which means that water can move through them between 50 and 1000 m/day, while grained silts and clays have low values in the range of 0.001–0.1 m/day. *Permeability* is a measure of the ease with which fluid will flow through a porous medium under a specified hydraulic gradient and is directly associated with infiltration capacity, but not with the fluid itself. Permeability is determined by the amount and size of pore space in the soil. Gravels typically have high porosities meaning that water flows easily through them, while silts and clays tend to have low porosities. Groundwater flow can also deliver contaminants to waterways. The *hydraulic gradient* is what causes water to move underground. It depends on the difference in hydraulic head (pressure and gravitational energy) between two different points. It is calculated as the change in head between those two points divided by the distance between them over the flow path. Of these three factors, hydraulic conductivity generally has the most effect on groundwater velocity [15].

6.3 Water Quality Dynamics

6.3.1 Stream Metabolism

Lotic (flowing) ecosystems such as streams, rivers, and estuaries are composed of abiotic and biotic parts that interact to perform ecological work [21]. This can be quantified in a holistic way by measuring the stream metabolism commonly done by monitoring changes in dissolved oxygen (DO) over a diurnal (daily) cycle [22–24]. Over the course of a day, DO increases during daylight due to primary production (photosynthesis by plants) and declines at night due to respiration (by the entire community of plants, animals, bacteria, fungi, etc.). Diffusion of oxygen between the water surface and atmosphere must be taken into account; this can be done either by direct measurements of gas exchange or by use of standard models that require information on stream channel dimensions and *discharge* (how much water over a time period passes a given point in the stream). Oxygen and other water quality parameters (e.g., temperature, conductivity, and turbidity) can be monitored at a high temporal resolution with data-logging sondes.

6.3.2 Water Quality Issues

Nutrients and suspended sediments have been identified as major sources of water quality degradation and are often monitored and evaluated as primary indicators of biochemical characteristics of water [20, 25–27]. Agricultural runoff from pastures and farmlands as well as human and industrial wastewater are common sources of nutrient pollution. *Nutrient pollutants*, primarily nitrogen and phosphorous, can stimulate the aquatic primary productivity rate, resulting in eutrophication of surface waters and consequent algae blooms. Increased aquatic productivity can ultimately result in depletion of DO levels in water, posing threats to aquatic organisms and adversely impacting stream metabolic processes [20]. *Sedimentation* can be defined as the process of inorganic or organic particles transported, suspended, and deposited in streams or lakes by gravity. The principal sources of sediments are upland erosion from overland flow and weathering. Excessive amounts of suspended sediment can reduce *water clarity* (a measure of the amount of light penetration in water) and hence affect plant photosynthesis. Deposited sediment can clog fish spawning beds and damage aquatic habitats [28–30]. Sediments transported through runoff often carry a significant loading of nutrients and toxic chemicals to water bodies and consequently impair their water quality [27].

6.4 Urbanization and Climate Change Implications

6.4.1 Urban Hydrologic Systems

There is a long history of building cities on or near rivers in order to have access to clean drinking water, and navigable waterways that provided a means for transportation/trade, and conveyed wastes away from the city. Urban development in the United States, which proceeded rapidly following the World War II and accelerated over the last three decades, has induced an expansion of impervious areas (cement and asphalt through which water does not flow) and a rapid reduction in natural vegetated areas. As a result, the natural hydrologic cycle shifts from an infiltration- and evapotranspiration-based system to a surface runoff-dominated system [30–33]. During the past half century, to accommodate the growing water demand in the face of increasingly limited freshwater resources, more than 30,000 large dams have been built globally as a common practice for securing water for municipal water supply, hydropower, irrigation, etc. [34, 35]. Some of these hydraulically modifying structures can alter the natural streamflow pattern substantially by following various management protocols such as a drought response plan that may hold back water, allow minimum release, and/or manage for downstream ecological flow requirements [34, 36, 37].

In urban hydrologic systems, instead of water running its natural course, streams that were once natural may now be channelized into artificially modified or constructed stream beds. Runoff from roofs and street surfaces may be diverted to the storm sewer system through storm drains, pipes, and ditches, creating various types of storm sewer systems, including *combined sewer system* (CSS), *sanitary sewer system* (SSS), and *municipal separate stormwater sewer system* (MS4). Storm and sewer systems were constructed as a means of dealing with two consistent problems in cities: (1) how to get rid of large amounts of wastewater and (2) how to protect property and lives from flooding particularly during large storm events. Most of today’s sewers were constructed in the late nineteenth and early twentieth centuries. CSS pipes collect sanitary sewer and stormwater flows together and route them to a wastewater treatment facility. SSS is designed to collect and transport only sewage from domestic, commercial, and industrial buildings to a wastewater treatment system. MS4 refers to a system that collects and discharges stormwater directly to

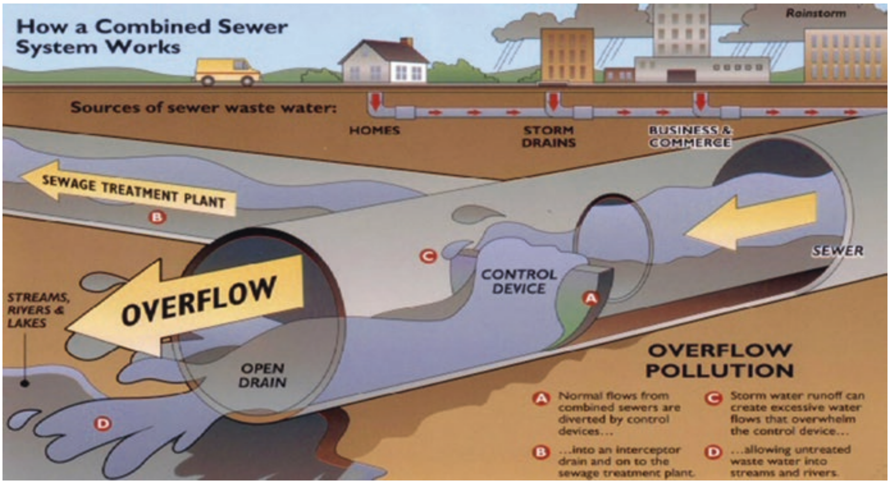


Fig. 6.2 In a combined sewer overflow (CSO), where during high-volume precipitation or snowmelt events, a gate opens automatically and releases stormwater mixed with sanitary effluent from the combined sewer system (CSS) and sanitary sewer system (SSS) trunk lines directly to urban lakes, rivers, and streams (Source: www.moundsvillewwtp.com/CSOs.html, with permission of Superintendent Larry Bonar)

surface waters. During low-flow periods, sewage from CSS and SSS is routed to a wastewater treatment facility. However, during large magnitude rainfall or snowmelt events, when stormwater runoff exceeds the capacity of the wastewater treatment system and/or the pipes, the surplus volume is released into neighboring surface waters, through large doors that open under pressure. These are often referred to as *combined sewer overflow* (CSOs) (Fig. 6.2) and *sanitary sewer overflow* (SSOs).

Water quality as well as quantity along a stream can be significantly affected by the location and timing of return flow through sewage effluent. Elevated pollutant concentrations found in urban runoff are directly related to the degree of urbanization, which increases runoff volume and peak flow rates [38, 39]. As stormwater flows over impervious surfaces, it often picks up a variety of pollutants produced from diverse human and industrial activities, e.g., pet waste, pesticide used for controlling insects and weeds, and petroleum pollutants from parking lots. These pollutants along with the stormwater runoff enter storm sewers and nearby water bodies contributing to elevated concentrations of pollutants in the water. Stormwater runoff of large magnitude contributes greatly to another major source of water pollution: sediment pollution. After a major rainfall event, runoff of large volume may wash loose soil off impervious surfaces into the lakes and streams posing a threat to aquatic organisms and plants [40, 41].

6.4.2 Urban Stream Metabolism

Because many cities are located along flowing waters, sewer overflows following high-flow events can have adverse impacts upon these ecosystems and their biota because these waters are used to receive both pre- and post-treatment effluent. Typically the sewage water delivers large amounts of organic matter and nutrients into the recipient water. Downstream, bacteria decompose the organic matter and deplete the oxygen, often severely. If one were to measure DO upstream of a CSO, and then downstream at various distances, one would observe a marked depression in DO just downstream of the CSO, followed by a gradual recovery of DO. This is referred to as a “dissolved oxygen sag” and is part of the classic urban stream pathology.

A good example of the effects of urban impervious surfaces and the impacts of CSOs can be seen by comparing two sites along a typical urban stream in a small- to mid-sized temperate city: Onondaga Creek in the city of Syracuse, NY. The upstream site is channelized, but the surrounding region is relatively open with forests and suburban lawns. The downstream site is within downtown Syracuse with almost complete impervious cover. The differences are greatest during storm events. During low-flow (dry) summer conditions, DO shows typical cycles of peaks in the daytime and minima at night (Fig. 6.3a). However, during a period of rainstorms, the peak/trough pattern of DO is greatly reduced, and in the CSO region of the downtown, it is essentially extinguished (Fig. 6.3b).

Ecosystem metabolism is a rate measurement, and so we need to integrate the rate of change of DO after accounting for diffusion, as in Fig. 6.4. Doing that, we see that the daytime peak in dry weather productivity is slightly shifted in the city vs. upstream (rural) site (Fig. 6.4a), but otherwise the dynamics are similar. During the storm period, oxygen changes quickly both upstream and downstream (left side of Fig. 6.4b), but the variations are much exaggerated in the more urban part of the stream. Both sites were affected by the clouds and rain, but the runoff response of the city area is truly “flashy.” Thus, we can conclude that during dry periods, the stream behaves in a similar way regardless of surface cover, but in wet periods the concrete urban surfaces and enhanced runoff greatly affect the stream.

Stream turbidity (cloudiness) is an interesting corollary to the dissolved oxygen dynamics in this example. Turbidity is correlated to sediment load, as it is partly caused by the particles suspended in the water column. The Onondaga Creek is a turbid stream due to groundwater upwelling upstream. In low-flow conditions, the upstream, relatively rural site is more turbid, but we also see a diurnal pattern of rise and fall in turbidity (Fig. 6.5a). The peak in turbidity at night when DO concentration is lowest might be accounted for by animal activity. During storms, the impervious surfaces of the city wash all the surface grit down into the CSOs from where

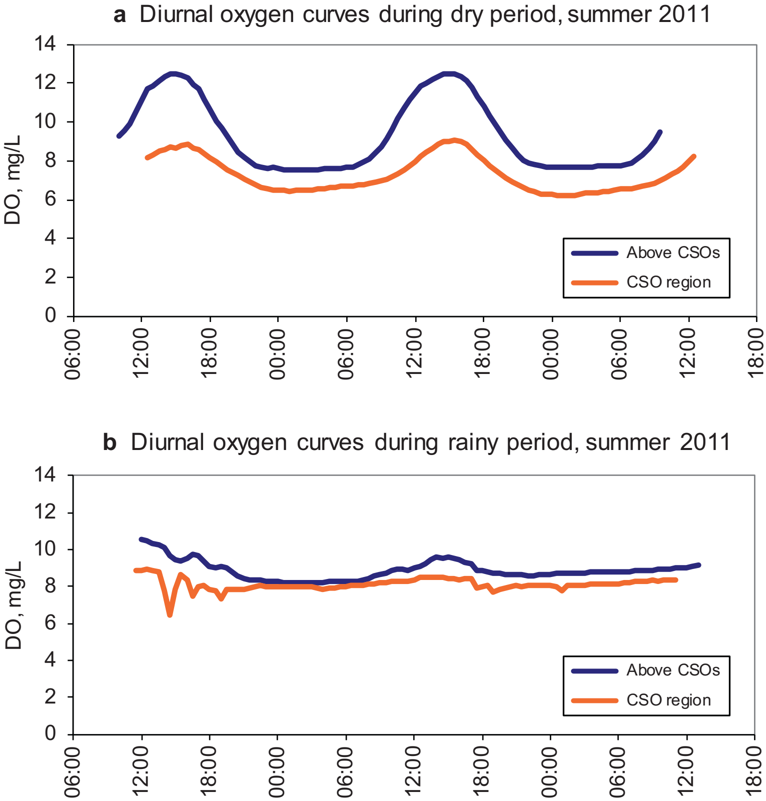


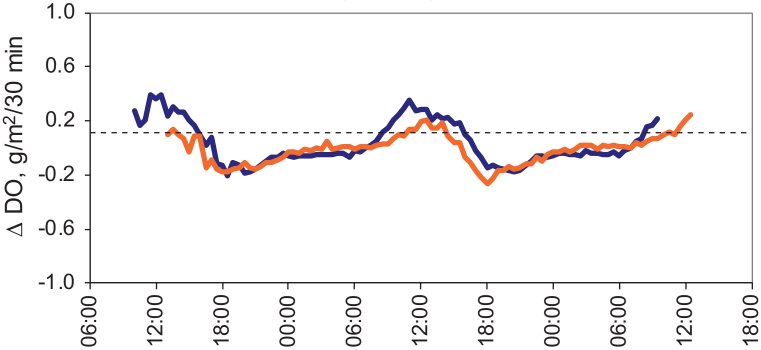
Fig. 6.3 Comparison of DO curves, between CSO and non-CSO sites along the Onondaga Creek during (**a**) dry period and (**b**) rainy period of Summer, 2011

they are released to the creek along with accumulated silts, which have been accumulating behind the CSO door, and are also resuspended (Fig. 6.5b) because of the high flows, creating "turbidity spikes." The ecological effect of such spikes is unclear but is likely stressful to fish and other aquatic life.

6.4.3 Climate Impact on Urban Hydrologic Systems

Water resources are under increasing stress in many regions across the world from altered hydrologic, thermal, and water quality conditions resulting from changing climate [40, 42–44]. The frequency of heavy precipitation events has increased by about 20% on average in the United States since 1958. The increasing trend of extreme precipitation events is expected to continue in the future, with likely intensification over much of the United States [45, 46]. The heavy rainfall events have

a Rate of DO change during dry period, summer 2011



b Rate of DO change during a rainy period, summer 2011

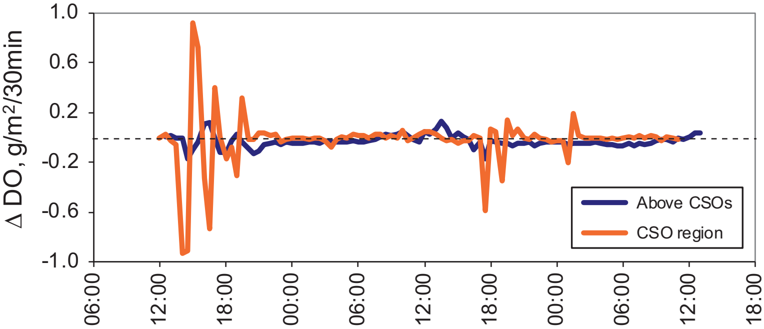
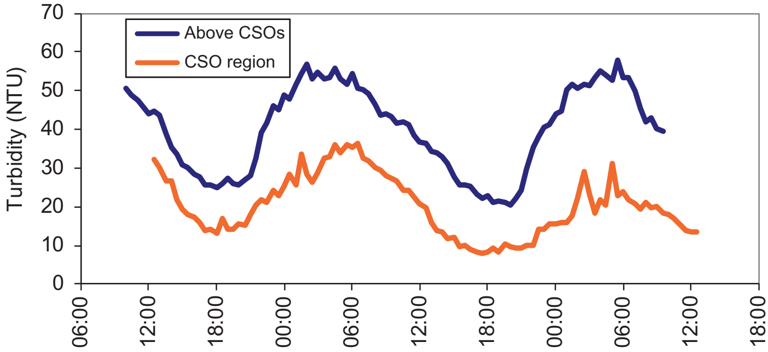


Fig. 6.4 Rate of DO change in CSO vs. non-CSO sites along the Onondaga Creek during (**a**) dry period and (**b**) rainy period of Summer, 2011

posed substantial risk to urban drainage infrastructures that are mostly designed to handle the design storms of 50 years and more ago. While extreme rain events are often the cause of extreme flood events, an increasing number of large flood events are associated with snowmelt from deep snowpack especially during *rain-on-snow* (ROS) events in many snow-fed rivers across the western United States [8, 47]. The ROS events, typically occurring with warm temperature and high winds, significantly accelerate snowmelt and can produce severe flood events both in the mountainous regions and lowlands. The warming trend of air temperature over the last century has led to changes in mountain snowpacks that are well documented in many parts of the United States [6, 7, 40, 42, 43, 47–49]. The projected increase in average temperatures across the country will reduce the proportion of precipitation falling as snow and lead to a shorter duration of snow cover causing a shift of snow regime. Early occurrence of snow melt and lack of adequate spring melt would lead to declined stream flows in late spring and summer and impose profound stress for both cities and the ecosystems in which they are embedded. This is especially true for cities in snowmelt-dominated regions that are subject to dry summers when water demand is also greatest, such as in much of the western United States.

a Turbidity during dry period, summer 2011



b Turbidity during rainy period (CSOs), summer 2011

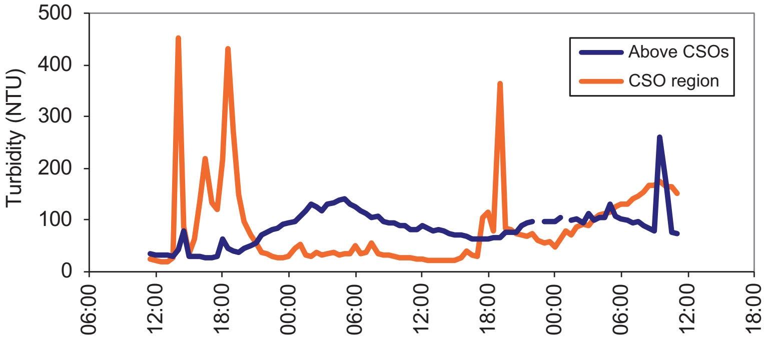


Fig. 6.5 Comparison of turbidity in CSO vs. non-CSO sites along the Onondaga Creek during (**a**) dry period and (**b**) rainy period of Summer, 2011

Rapid urbanization will exacerbate impacts on urban streams from climate change in a number of ways. (1) Hurricanes fed by warmer oceans will bring heavier rainfall. Urban development on water-absorbing wetlands as was done in Houston, TX, or expanding development on mountain slopes above cities like San Juan, Puerto Rico, exacerbates the flooding associated with the extremely heavy rainfall accompanying 2017 hurricanes Irma and Maria. Coastal cities will see more impactful storm surges that flood streets, homes, and drainage systems. (2) Temperature in urban small streams, in comparison to large rivers, is more susceptible to air temperature increases due to their relatively low heat capacity, particularly during low-flow summer conditions [40, 44]. Elevated water temperature can negatively impact the stream water quality, as well as the physical, chemical, and biological health of aquatic ecosystems. It is worth mentioning that the thermal input from paved surfaces is a main contributor to abruptly increased water temperature in urban streams during rain storms [44]. Finally, reduced surface water resources due to drought or timing of snowmelt will encourage human intervention in water use, for example, reservoir construction and regulation, water conservation measures, and statewide emergency water shortages such as in Los Angeles during California's long drought of 2011–2017. Lastly, changing climate is anticipated to have substantial impacts for energy production. About 66% of electricity generation in the United States requires water for cooling, and about 40% of freshwater withdrawal is required for thermoelectric production in the United States. Due to environmental restrictions on availability of cooling water and on warm water discharges back into rivers, the projected lower water availability and higher surface water temperature in the future would have great implication for the electricity sector across the world including the United States [50].

6.5 Remediation Technologies

6.5.1 Green Infrastructure

As discussed earlier, CSOs are a major problem for urban systems during storm events. Once the sewage effluent and street runoff are combined, the contaminants in the sewage will pollute the receiving water. This poses a considerable threat to both the ecological metabolism of the city aquatic life, human health, and groundwater quality and to the sociological quality of neighborhood life and economic activity that may rely on receiving waters for tourism, fishing, recreation, and real estate values, hence greatly affecting the city's overall metabolism. The traditional solution to CSOs is installation of *grey infrastructure* (e.g., sewage treatment plants and underground storage tanks) or enlargement of current treatment facilities to enhance their storage and conveyance capacities. The cost of conventional approaches, however, often exceeds the affordability standard for stormwater management or is limited by land availability in the already tightly structured urban landscape. More importantly, the conventional solution cannot be considered sustainable because it does not treat the runoff volume or stormwater-carried pollutants at the source nor address the problem of groundwater depletion that occurs because precipitation cannot infiltrate urban soils that lie under the buildings and pavement [39, 51].

Green infrastructure (GI), on the other hand, offers cities and communities a more cost-effective opportunity to achieve CSO mitigation requirements. GI technologies consist of decentralized structures that have the potential to capture, retain, infiltrate, evapotranspire, and reutilize the stormwater runoff. GI structures at the parcel scale (meaning an individual household, apartment building or commercial lot) include rain gardens and bioretention cells, rain barrels, green roofs, and porous paving. *Rain gardens* and *bioretention* cells are vegetated depressions receiving stormwater runoff water from rooftops or other impervious surfaces such as driveways along the flow path (see Fig. 15.11). Soils in the rain gardens and bioretention cells often have a higher infiltration capacity and a saturated hydraulic conductivity rate that allows for water retention. Instead of flowing to a street or into the storm drains, the detained stormwater is either evaporated and transpired by plants or percolates into the soil's unsaturated zone where it will contribute to groundwater recharge. The plants and mulch in rain gardens and bioretention installations can also trap and even remove the pollutants from runoff through physical, biological, and chemical processes. *Rain barrels* operate as detention tanks, which are usually placed underneath rooftop downspouts. They collect rainwater from rooftops for reuse such as irrigation. *Green roofs* are rooftops which are planted with a vegetation layer (see Fig. 15.10). There are two types of green roofs: (1) extensive roofs, which are constructed with a minimal soil layer of less than 6-inch thickness and support primarily dense, low-growing and drought-resistant vegetation, and (2) intensive roofs, which have a thick layer of soil of greater than 6-inch and can support all types of vegetation. Green roofs have many benefits. They can reduce the stormwater runoff and enhance water quality by capturing rainwater and filtering the pollutants in rainwater. Green roofs can also cool the rooftop and surrounding air through both less retention of solar radiation (see Chap. 7) and evapotranspiration, thereby reducing cooling demand in summer. *Porous paving* is an alternative to conventional impervious asphalt or concrete surfaces. It allows stormwater to infiltrate through the pavement and percolate into the underlying subsoil promoting groundwater recharge. Compared to CSO storage and conveyance systems, GI may cost less to implement than grey infrastructure solutions (comparisons should be conducted before a decision is made (see Chaps. 1 and 15)) and has lower operation and maintenance (O&M) costs since plants, if well chosen (see Chap. 11), do the work. GI also helps reduce CSO events and water pollution potential by capturing pollutants and treating stormwater onsite before it enters the storm drains. Additional benefits include promoting infiltration and groundwater recharge, restoring water bodies, improving air quality, mitigating the heat island effect, sequestering carbon, and contributing to pleasant landscapes for the living environment.

6.5.2 Phytotechnology

Lastly, we would like to briefly introduce an emerging technology, *phytotechnology*, which consists of a set of technologies using plants to remediate or take up contaminants in soil, groundwater, surface water, or sediments. As plants play a significant role in the regional and local water cycle, phytotechnology is often operated on a catchment scale. Most common and widely applied phytotechnologies include phytostabilization, phytohydraulics, phytoextraction, and phytovolatilization [52, 53]. *Phytostabilization* controls infiltration by promoting interception and evapotranspiration by plants and subsequently lowers the groundwater table locally and limits contact of shallow-contaminated soils with groundwater. *Phytohydraulics* uses the ability of plants to evapotranspire surface water and groundwater. *Phytoextraction* refers to the use of pollutant-accumulating plants that can extract and translocate contaminants to the harvestable parts. Translocation of contaminants from the roots to the shoots is powered by leaf transpiration. *Phytovolatilization* refers to the process whereby plants extract and transpire volatile organic contaminants from media such as soil, groundwater, and sediment into the atmosphere.

Generally speaking, phytotechnologies have the following advantages: (1) cost-effectiveness compared to conventional techniques, e.g., off-site clean up, digging, and chemical treatment; (2) sustainability, because as opposed to conventional techniques, phytotechnologies provide continuous, long-lasting, and “free” (provided by nature) treatment to a wide range of contaminants, e.g., volatile organic compounds (VOC), heavy metals, and petroleum hydrocarbons; and (3) protection from soil erosion [54]. On the other hand, the phytotechnology applications are subject to the following limitations: (1) They can treat only sites with lower contaminant concentrations and contamination in shallow soils and groundwater. (2) The choice of plants is limited by local weather features. (3) Some applications based on plant evapotranspiration may be seasonal and not applicable during the winter period. (4) Some phytotechnology measures, e.g., constructed wetland and tree barriers, require a large surface area of land and may take longer than traditional methods to reach final cleanup levels.

6.6 Conclusion

A comprehensive understanding of the urban hydrological system is vital for developing sustainable and reliable water management/adaptation practices in urban areas that are vulnerable hotspots of climate change. This chapter provides an overview of the hydrological cycle, including the influence of meteorological, physiographic, and human factors on key aspects of the cycle, as well as water quality, in the urban context. Urbanization, coupled with projected warming air temperatures and more frequent extreme precipitation events due to climate change, is anticipated to impose greater challenges to water resources across multiple water uses including municipal water supply, agricultural demand, energy production, and environmental flow for sustainable ecosystem functioning. We discuss the common and emerging remediation practices for accommodating the potential changes in urban hydrological systems. Lastly, it should be emphasized that a systematic and interdisciplinary approach is required to study the urban hydrological system.

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Chapter 7
The Climate System

Gordon M. Heisler and Anthony J. Brazel

Abstract Interesting but sometimes complex interacting processes cause differences in climate between more urbanized areas and nearby less urbanized areas. This chapter aims to provide an understanding of urban climate systems and the ecological significance of the differences between rural and urban climate. We include explanations of terms, units of measurement, and basic equations that are commonly used in the expanding scientific literature from urban climate research around the world. We describe the physical processes that govern energy balances of urban landscapes—human-caused heat input; modified solar and thermal radiation; transfer of sensible heat, which we feel as air temperature differences; and movement of heat by evaporation and condensation of water. The urban effects on energy transfer and the flow of air in the lower layers of the Earth's boundary layer cause temperature differences between urban and rural areas known at the urban heat island (UHI) effect, which can commonly reach intensities of 10 °C. This effect is a main focus of the chapter. UHIs are altered by topographic influences that sometimes overwhelm urban land cover influences on air temperature. We describe types of UHIs and provide examples, the methods used to detect UHIs, and the influences of tree cover and parks. We briefly describe the effects of urban structure on wind, including thermally driven flow. Finally, we relate urban climate to global climate change and explore some of the difficulty of separating urbanization influences from global climate change.

Keywords Heat island · Land cover · Parks · Urban boundary layers · Urban forests

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7.1 Introduction

The goal of this chapter is to describe climatic conditions and processes that are different in urban areas from those in other landscapes—agricultural, grass land, or forested. Urbanization modifies all of the variables that make up weather and climate—air temperature, humidity, wind, precipitation, cloud cover, and both thermal and solar electromagnetic radiation. Of these variables, the one that is generally most obvious and probably the most studied is the presence of temperatures that differ from those in nearby rural areas. Within cities, temperatures are generally, though not exclusively, warmer [1].

In contrast to global climate change, which is somewhat hard to detect because it has effects over large parts of the Earth over long time periods and is more difficult to measure, the influence of cities on temperature in and near them is relatively easy to determine. In the case of global climate change, it is somewhat difficult to determine whether change is caused entirely by human activity or partly by processes that would take place without people. The cause of urban influences on climate is obvious—human-built structures and activity—and these produce radically altered local environments [2]. In many cities, global environmental changes are swamped by dramatic changes in the local environment [3]. In this chapter we explore these changes, especially to temperatures, as background for discussion of broader urban ecology, which integrates natural and social sciences generally and in other chapters in this book. The ecological considerations are important because cities create both the problems and solutions to sustainability challenges in our increasingly urbanized world [2].

Generally increased temperature in cities compared to nonurban areas, termed the *urban heat island* (UHI) effect, is present in cities all around the world and contributes to global climate change in several ways. In turn, the effects of UHIs are increased by global climate change [4, 5]. In an energy-constrained future, the importance of urban temperatures will increase in many climates, because high temperatures lead to greater energy use for air conditioning. This is especially true in climates in which buildings can be cooled by opening windows to reduce reliance on air conditioning, because there will be fewer hours of cool outside air [6]. The UHI effect creates one of the key challenges to evaluating the influence of *greenhouse gases*[1] on global climate change, because urban influences are present in archived historical weather data that are used to determine long-term climate trends [7].

One goal of this chapter is to present some of the terminology that is commonly used in the scientific literature about urban climate. Both *meteorology*, the instantaneous or short-term processes in the atmosphere, and *climate*, the longer-term average, maximum, and minimum values of atmospheric features, may be described at a large range of spatial scales. Urban atmospheric processes are usually described at

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[1] Carbon dioxide, methane, and other gases that are transported from sources near the ground into the upper atmosphere and act to intercept longwave radiation from the Earth's surface.

Table 7.1 Scales used in descriptions of atmospheric processes [8]

Scale name	Range of length	Typical area
Microscale	10^{-2} to 10^{3} m	Single family home patio to a city block
Local scale	10^{2} to 5×10^{4} m	Several city blocks to the size of a small city
Mesoscale	10^{4} to 2×10^{5} m	A large city to one or two states
Macroscale	10^{5} to 10^{8} m	Weather-map-sized areas, whole continents

the *microscale* or *local scale*, and sometimes at the *mesoscale*, where the overlapping horizontal ranges of the scales are given approximately as in Table 7.1. Weather forecasting is done with consideration of conditions at the *mesoscale* and *macroscale*, sometimes referred to as the *synoptic* scale.

Urban meteorological and climatic impacts include effects on human health and comfort, energy use for space conditioning of buildings, air pollution, water use, plant growth and other biological activity, ice and snow, precipitation and flooding, and even environmental justice. In this chapter we emphasize urban climatic influences and processes that affect the urban air temperatures. We especially consider those influences that are most likely to be modified by urban design or management. Examples include the amount and distribution of park land and other open space, tree and other vegetation within the open space, overall distribution of vegetation within developed portions of the city, the use of irrigation to maintain vegetation, and "urban whitening," changing the reflectivity of pavements or roof surfaces by reflective paint or construction with reflective materials.

In following sections, the basic energy transfer processes of any landscape are described—radiation, sensible and latent flux,[2] and storage in soil and vegetation. This leads to the notation used to describe landscape energy budgets. With the energy budget concept in mind, the following sections consider urban influences on the energy budget, urban influences on the atmospheric boundary layer, and urban interactions with topographic influences including water bodies. Then we provide examples of urban heat islands, the methods used to detect them, and the influences of tree cover and parks. We briefly describe the effects of urban structure on wind, including thermally driven flow. The important concerns related to urban influences on meteorology and climate come next—human comfort and health, energy use in buildings, and precipitation. Finally, we relate urban climate to global climate change and explore some of the difficulty of separating urbanization influences from global climate change.

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[2] A "flux" is the transfer of some quantity, such as an amount of energy, per unit time. Energy may be measured in joules (J), and 1 J per second, J s^{-1}, is 1 W. Thus, the unit watt (W) is a flux. Flux density is flux per unit area, such as the number of watts through an area of 1 m^{2}, W m^{-1}.

7.2 Physical Processes in Climate Systems

7.2.1 Radiant Energy Exchange

The energy that causes what we call climate begins with the sun. The sun's energy comes to Earth as *electromagnetic radiation*.[3] All objects give off electromagnetic radiation, which can be conceptualized as having waves with a peak-to-peak length that depends upon the temperature of the object's surface. The temperature at the surface of the sun is about 6000°K,[4] and the electromagnetic radiation from the sun that gets through Earth's atmosphere has a peak within the human visible range of wavelengths, which is about 400–700 nanometers[5] (nm). The total range of the solar spectrum on Earth is from 280 nm to about 3000 nm (or 0.28 micrometers, abbreviated μm, to 3 μm), and we call this whole range *shortwave* or *solar* radiation.

Surfaces with temperatures near those we commonly encounter around us in cities, about 300°K, emit radiation in the spectrum from about 4 to 30 μm. We call this *longwave* or thermal radiation. The intensity of radiation per μm and per unit area is about 10,000,000 times greater in shortwave (S) than longwave (LW) radiation. When incoming shortwave radiation, $S_\downarrow$, strikes an object, it may be either absorbed or reflected. The fraction of $S_\downarrow$ reflected is called the *albedo* of that surface, often abbreviated by α. In mathematical form, absorbed shortwave radiation is given by

$$S_{\text{abs}} = (1-\alpha)S_\downarrow \tag{7.1}$$

Generally, the lighter the color is, the higher the albedo. The urban whitening method proposed for cooling cities uses paint or special roofing or paving materials to increase α of the city, so that S_{abs} is lower and less shortwave radiation is available to heat the city [9].

The rate of radiation emitted by a surface depends upon the temperature of the surface and a characteristic of the material, the *emissivity*, ε, which is the amount of radiation emitted relative to the amount that would be emitted by a black body[6] for a given temperature. Most materials in nature have an ε of about 0.95. The governing equation for emitted longwave radiation is

$$\text{LW} = \sigma\varepsilon T_K^4 \tag{7.2}$$

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[3] Electromagnetic radiation is energy transfer through space by disturbances in electric and magnetic fields that can be described as waves that have different wavelengths of oscillation in a continuous spectrum.

[4] In the Kelvin scale of temperature, 0 °K is absolute 0 and it is identical to −273.15 °C.

[5] In meteorology and climatology, the spectrum of solar electromagnetic radiation is commonly measured in nanometers, 1 nm = 0.000000001 m (1×10^{-9} m). The spectrum of thermal radiation is commonly measured in μm, 1 μm = 0.000001 m (1×10^{-6} m).

[6] A black body is a conceptual opaque and non-reflective object that is perfectly absorbing longwave radiation and emits at the same rate.

where σ is a constant, called the *Stefan-Boltzmann constant* and T_K is Kelvin temperature of the surface. Thus, longwave radiation from the sky toward the ground, $\mathrm{LW}_\downarrow$, is $\sigma\varepsilon_a T_K^4$, where ε_a is atmospheric emissivity. Longwave radiation from the ground surface, $\mathrm{LW}_\uparrow$, is $\sigma\varepsilon_e T_K^4$, where ε_e is emissivity of the Earth or ground surface. The ε of a surface also governs its absorbance of incoming longwave radiation.

We now have the components that make up an important part of the explanation of climate of a city, or any other area—the net radiation, Q^*, the total short and longwave radiation absorbed by the Earth surface, which in equation form is

$$Q^* = S_{\mathrm{abs}} + \mathrm{LW}_\downarrow - \mathrm{LW}_\uparrow. \qquad (7.3)$$

The symbol Q with a superscript or subscript letter or symbol is commonly used to represent a heat flux in energy budget equations.

On cloudy nights, T_K of the sky and ground surface are similar, so that $\mathrm{LW}_\downarrow$ and $\mathrm{LW}_\uparrow$ are nearly equal. However, on cloud-free nights, the effective T_K of the sky may be much less than T_K of the ground surface, so that rapid cooling of the surface results.

7.2.2 Heat Flow

Heat flows into and from air in two forms. When air absorbs or gives up heat and air temperature increases or decreases, the amount of heat is termed *sensible heat*, heat you can feel. If liquid water evaporates to become vapor in air, energy is required to evaporate the water, and that energy is termed the *latent heat of vaporization*. This heat energy is contained within the vapor. The reason it is called "latent" (potential but not evident) is that when air is cooled below a certain temperature, which depends on the amount of vapor in the air, vapor condenses and gives up the latent heat. The lower the temperature at which condensation begins (*dew point temperature*), the drier the air. The latent heat of vaporization, about 2.5 MJ/kg of water evaporated, is a major factor in determining climate, because it uses energy from Q^*. The more Q^* is used in latent heat production, the less Q^* is available for sensible heat creation. Latent heat production has the potential to consume a large amount of Q^*. It takes nearly six times more energy to evaporate 1 kg of water than it takes to heat 1 kg of liquid water from 0 °C all the way to 100 °C.

When the surface temperature changes, energy flows into and out of soil, rock, plant material, or human-made objects like roads and buildings in response to temperature differences between the surface and the interior of the substance. This is termed heat *storage*. For a given temperature difference, the rate of flow depends upon the thermal properties of the material (Table 7.2). *Density* is simply mass, the amount of "stuff," per unit of volume, and though density affects the thermal properties, it is not itself considered one of the thermal properties. *Thermal conductivity* is the ability to conduct heat, the quantity of heat (in units of joules, J) flowing through a cross sectional area (m^2) each second (s) if there is a temperature gradient

Table 7.2 Thermal properties of typical urban interface materials [8]

		Specific	Heat	Thermal	Thermal
	Density[a]	Heat, *c*	Capacity, *C*	Conductivity, *k*	Admittance, μ
Material	Kg $m^{-3} \times 10^3$	J kg^{-1} $K^{-1} \times 10^3$	J m^{-3} $K^{-1} \times 10^6$	W m^{-1} K^{-1}	J m^{-2} K^{-1} $s^{-1/2}$
Urban materials					
Asphalt	2.11	0.92	1.94	0.75	1205
Brick	1.83	0.75	1.37	0.83	1065
Concrete	2.40	0.88	2.11	1.51	1785
Glass	2.48	0.67	1.66	0.74	1110
Steel	7.85	0.50	3.93	53.3	14,475
Natural materials					
Air (20 °C)	0.0012	1.01	0.0012	0.025	5
Sand (dry)	1.60	0.80	1.28	0.30	620
Soil (dry clay)	1.60	0.89	1.42	0.25	600
Soil (wet clay)	2.00	1.55	3.10	1.58	2210
Water (20 °C)	1.00	4.18	4.18	0.57	1545
Wood, light	0.32	1.42	0.45	0.09	200

[a] The values for density, specific heat, and heat capacity are scaled by the exponents of 10 to keep them to an easily handled size in the table. For example, for asphalt the density is 2110 kg/m^3, and heat capacity is 1,940,000 J/m^3 for each 1 °K of temperature change

(1° K m^{-1}, or 1-degree Kelvin per meter) perpendicular to the area. The units J s^{-1} (joules per second) are equivalent to 1 watt (W), so the units given in Table 7.2 for thermal conductivity are W m^{-1} K^{-1}. The temperature change (K^{-1}) in a given mass of a material for a given amount of heat absorbed (J) depends upon the *specific heat*, *c*, with units of J kg^{-1} K^{-1} when considering the heat required for a unit of mass (kg) or when considering heat required per unit volume, the *heat capacity*, C, with units of (J m^{-3} K^{-1}).

Thermal admittance, μ, of a surface is especially interesting for urban climate because it determines the amount of heat (J) that will pass from the surface into the material for a given heat source. Though the units are somewhat difficult to grasp intuitively, the effects of μ are easy to feel. For example, nearly everyone has the experience of feeling the hot sand when walking barefoot across a beach of dry sand. Dry sand has low thermal admittance, and it gets very warm because little of the absorbed heat from the sun is carried into lower layers of the sand. Another intuitive appreciation of thermal admittance comes from touching two materials—one of steel the other of wood—with the same temperature, say 20 °C, room temperature in a building. Because of its extremely high thermal conductivity, the steel has high μ (see Table 7.2) and will feel cool because it rapidly removes heat from your finger, which is at skin temperature of about 30 °C, whereas wood, with low μ, will transmit little heat from your finger and feel relatively warm to the touch [8]. Materials with high admittance tend to store large amounts of heat during the day and release it at night—one of the effects that makes urban areas warmer than rural. Thermal admittance is proportional to conductivity and heat capacity. It can be calculated from columns 4 and 5 in Table 7.2 as $(k \times C)^{1/2}$. Note in Table 7.2 that most urban materials (except for wood, which could also be considered an urban material) have high μ compared to the natural materials, except for water and wet soil.

An implication for urban design is that night-time cooling will be enhanced if the surface is covered by low-admittance materials. However, if low-admittance surface materials cannot be used, greater cooling will occur if sky view (the percent of sky visible above a point on the ground) is greater, for example, with wider spacing between buildings. Cooling increases with increase in sky view unless μ is very low [10].

7.2.3 *Energy Budget Concept*

The *energy budget* for an area on Earth is largely responsible for temperature differences between that area and other areas with different energy budgets. Symbolically, the energy budget for a surface, such as flat bare soil is

$$Q^* = Q_E + Q_H + Q_G \tag{7.4}$$

Here, Q^* is net radiation as in Eq. 7.3, Q_E is the flux of latent heat (latent heat of vaporization, see Sect. 7.2.2), Q_H is sensible heat flux, and Q_G is storage of heat in the soil. In most landscapes, Q_E results from evaporation from water bodies and soil or transpiration from plants, and we call the combined process *evapotranspiration*.

The energy budget concept may be applied to other surfaces—one side of a single tree leaf [11], the skin of a person [12], or the wall of a building [8]. Energy budgets may also be calculated for the upper surface of an agricultural crop, a forest, or a city, but, while the general level of the tops of trees or buildings may be considered to be a surface, there is actually a volume below that surface that contains the trees or buildings, and that volume may be visualized as an imaginary box [8]. Then the storage term, often designated as ΔQ_S, must include the heat storage within those trees or buildings in the volume in addition to the soil storage Q_G [13]. Another complication for the energy budget of such a volume, or "box," is that air can move into the box from the side, a process termed *advection*. Advection is usually assumed to be small relative to Q^*, an assumption generally necessitated by the difficulty of measuring advection.

7.3 The Urban Energy Budget

Urban influences on temperature differ from rural areas because of differences in their energy budgets. These energy budget differences are caused in part by differences in the properties of materials found in rural and urban areas. The different materials cause differences in total heat storage, ΔQ_S, which includes heat storage in aboveground objects as well as storage in the soil, Q_G. Another difference is that urban energy budgets have an additional component—human-produced heat sources or *anthropogenic* heat emissions, Q_F—that must be added to net radiation as a heat input [14]. With the new terms, the urban energy budget becomes:

$$Q^* + Q_F = Q_E + Q_H + \Delta Q_S \tag{7.5}$$

7.3.1 Anthropogenic Heat Sources

The methodology to evaluate the different sources of anthropogenic heat, Q_F in Eq. 7.5, in an urban energy budget is challenging but interesting [14]. Combustion heat has been estimated for some cities by analysis of consumer usage of fuel such as gas and electricity considering, for example, the number of vehicles, distance traveled, and fuel efficiency. Total anthropogenic emissions range from nil to 300% of net radiation, depending upon the amount of industrialization. Generally, Q_F is higher in more industrialized cities, in high-latitude cities, and in winter. It is composed primarily of heat produced by combustion of vehicle fuels, from heating and cooling buildings, and heat released from industrial processes. Even metabolism in human bodies can be a heat source, though it is generally <1% of total Q_F and can be ignored. There is a positive feedback loop between air conditioning and urban warming. As a city becomes warmer, increased use of air conditioning adds significantly to additional warming [14].

A mesoscale modeling study (see Sect. 7.6.5) of Philadelphia, PA, gives an idea of the importance of Q_F in urban energy budgets [15]. Summer anthropogenic heating ranged from about 20 W m^{-2} at night to around 50 W m^{-2} during the day. This compares with typical peak daytime solar radiation of around 700 W m^{-2}. During the day, Q_F had a negligible effect on air temperature, but it increased temperature about 0.8 °C at night. In winter the anthropogenic heating ranged from about 35 W m^{-2} at night to around 85 W m^{-2} during the day. The peak daytime solar radiation levels in winter were only about 460 W m^{-2}, much less than in summer. The Q_F heating in urban temperature simulations increased air temperature by 0.5–0.8 °C during the winter day and 2–3 °C during the winter night.

7.3.2 The Urban Radiation Balance

An urban area affects the exchanges of shortwave and longwave radiation by increased air pollution and by complex changes of surface radiative characteristics. The atmospheric attenuation (reduction of radiation by scattering and absorption) of incoming shortwave radiation by pollution has been analyzed in numerous urban environments. The attenuation in the atmosphere over cities is typically 2–10% more than in the surrounding rural areas. Generally, the very shortest wavelengths (<0.4 μm) of the electromagnetic spectrum to reach the surface of the Earth, the *ultraviolet* or *UVB* portion, are commonly depleted by 50% or more [16]. However, total depletion across all solar wavelengths (0.15–4.0 μm) is <10%. The processes of scattering and absorption are greatly modified by the urban aerosol characteristics and concentrations [17].

Another effect of urbanization is the change in albedo, which is typically slightly less in urban areas than in the surrounding landscape. Lower albedo is due in part to darker surface materials making up the urban mosaic and also to the effects of trapping shortwave radiation by the vertical walls and the urban, canyon-like morphology. There is considerable variation of albedo within the city depending on the vegetative cover, building materials, roof composition, and land use characteristics. The difference in albedo between a city and its surrounding environment also depends on the surrounding terrain. A city and a dense forest may differ a little in albedo; both may range from 10% to 20%. Urban trees lead to cooler cities because they store little heat and cool by evapotranspiration, not by having high albedo. In winter, a mid-latitude to high-latitude city with surrounding snow cover may display a much lower albedo than its surroundings. Thus, since cities receive 2–10% less shortwave radiation than their surroundings yet have slightly lower albedo (by <10%), most cities experience very small overall differences in absorbed shortwave radiation relative to rural surroundings [18].

Longwave radiation is affected by city pollution and the warmer urban surfaces. Warmer surfaces promote greater thermal emission of energy vertically upward from the city surface compared to rural areas, especially at night. Some longwave radiation is reradiated by urban aerosols back to the surface and also from the warmer urban air layer. Thus, increases in incoming longwave radiation and outgoing longwave radiation are usually experienced in urban areas. Outgoing longwave radiation increases are slightly greater than the incoming increases in the city, again especially on clear, calm nights. During daytime there is little difference between the city and its surroundings. Viewed from above a city, the overall surface emissivity can be different between country and city areas, and this may account for longwave radiation differences between urban and rural [19]. However, because a city structure is three-dimensional and variable, general statements about the overall urban versus rural emissivity and resulting effect on surface temperature of most cities cannot be made with confidence [20].

Longwave emission from soils and soil heat capacity are determined by soil moisture and hence by recent precipitation. Therefore, soil temperatures, and indirectly, air temperatures, depend upon precipitation [21, 22]. In a Baltimore study, air temperatures in rural landscapes became closer to urban air temperatures (smaller UHI) when recent precipitation was high.

7.3.3 *Urban Sensible and Latent Heat Fluxes and Heat Storage*

The partitioning of energy in urban areas among sensible (Q_H), latent (Q_E), and storage of heat (ΔQ_S and Q_G) primarily depends on the variety of land uses in the city compared to rural areas. Generally, the drier urban building and road materials induce higher Q_H, less Q_E, and higher ΔQ_S and Q_G in urban areas, all of which contribute to the UHI effect. However significant Q_E release does occur in many cities, because tree cover can be substantial, depending in part upon the general climatic region, with desert areas usually having lower tree cover (see Chap. 8). States in New England have average state-wide tree cover in their communities of 52–67%. Tree cover over some large cities such as Jersey City and San Francisco is about 12%, while Atlanta has about 37% tree cover. Especially in drier climates, Q_E is enhanced by irrigation [23, 24].

The value of Q_G and soil temperatures are greatly modified if asphalt covers the ground. In the soil of 2.5 m by 2.5 m tree planter boxes cut into the asphalt of a parking lot in New Brunswick, New Jersey, temperatures were compared to those in control planter boxes off the lot surrounded by grass instead of asphalt [25]. Near the center of the planter spaces on the parking lot, at a depth of 15 cm and 85 cm from the edge of the asphalt, maximum temperature exceeded controls by up to 3 °C. At the same depth but below the asphalt, maximum temperatures exceeded controls by up to 10 °C. Asphalt covering the soil not only increased maximum temperatures through a 60 cm profile but increased the rate of heat exchange since temperatures in the covered soil rose and fell more rapidly than control temperatures. In New Jersey, temperatures below the asphalt ranged from 0.5 to 34.2 °C, which was well within the toleration of tree roots. In contrast, temperatures below the asphalt of a parking lot in the warmer climate of Phoenix reached the likely plant-damaging temperature of 40 °C at a depth of 30 cm [26].

7.3.4 *Energy Budget Examples*

Measurements of above-canopy energy fluxes in Basel, Switzerland, over 30 days in midsummer (Fig. 7.1) illustrate the daily course of energy budgets at an urban, a suburban, and a rural location. Figure 7.1 uses the common convention that net fluxes toward the surface are positive, and fluxes away from the surface are negative. The net radiation, Q^*, is negative at night, meaning the net flux is upward, because $LW_\uparrow$ is greater than $LW_\downarrow$. Note the following: (1) in midday, the negative ΔQ_S means that heat is going away from the surface into storage, and positive ΔQ_S at night means heat is coming from storage toward the surface; (2) the magnitude of storage decreases from urban to rural; (3) sensible heat flux, Q_H, which is always negative, upward, is largest (most negative) in urban during the day and decreases in magnitude from urban to rural; and (4) latent heat flux (evaporation), Q_E, increases from

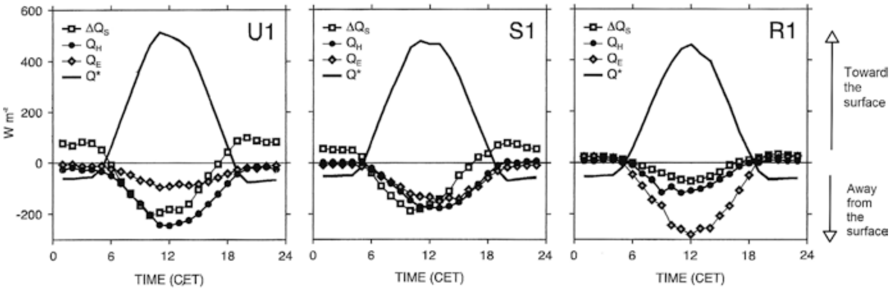


Fig. 7.1 Thirty-day average energy budgets for an urban site (U1), a suburban site (S1), and a rural site (R1) in or near Basel, Switzerland [27]

urban to rural. The partitioning of the net radiation, $Q*$, into greater storage, greater sensible heat, and less latent heat in the more urbanized land uses explains the UHI effect.

7.4 The Urban Boundary Layer

7.4.1 Structure and Dynamics

The next step to understanding urban climate is to consider the structure of the Earth's boundary layer in urban areas, or UBL. The UBL is a modification by cities to the *planetary boundary layer* (*PBL*), also known as the *atmospheric boundary layer* (*ABL*) as diagrammed in Fig. 7.2. The PBL is the lowest part of the atmosphere that is directly influenced by its contact with the Earth's surface. The PBL depth, which varies from about 100–3000 m, is controlled by the surface roughness, temperature, moisture, and injections of pollutants. Solar heating of the surface during the day creates buoyancy of air in touch with it, and the resulting turbulent mixing expands the PBL toward its maximum depth. At night, cooling at the surface by outgoing longwave radiation causes the air flow to become smooth and nonturbulent, and the PBL shrinks to a depth of as little as 100 m [29]. Note that in the conceptual city of Fig. 7.2, which has a sharp rural to urban boundary, the UBL increases in thickness beginning at the upwind edge, and the UBL extends some distance downwind in a plume.

The UBL is divided into several layers by structural and dynamical features. For decades, urban climatologists have used an analogy with rural forests to describe urban structure in terms of the urban canopy layer (UCL), the space generally below the tops of trees and buildings. In humid-climate forests, the active surface, where most of the exchange of radiant energy and turbulent transport of water vapor and heat takes place, is usually a layer from the tops of trees down to the point where tree crowns meet. Foresters think of the forest canopy layer as the space between the tops of tallest trees and the bottom of tree crowns that bear living foliage. The active

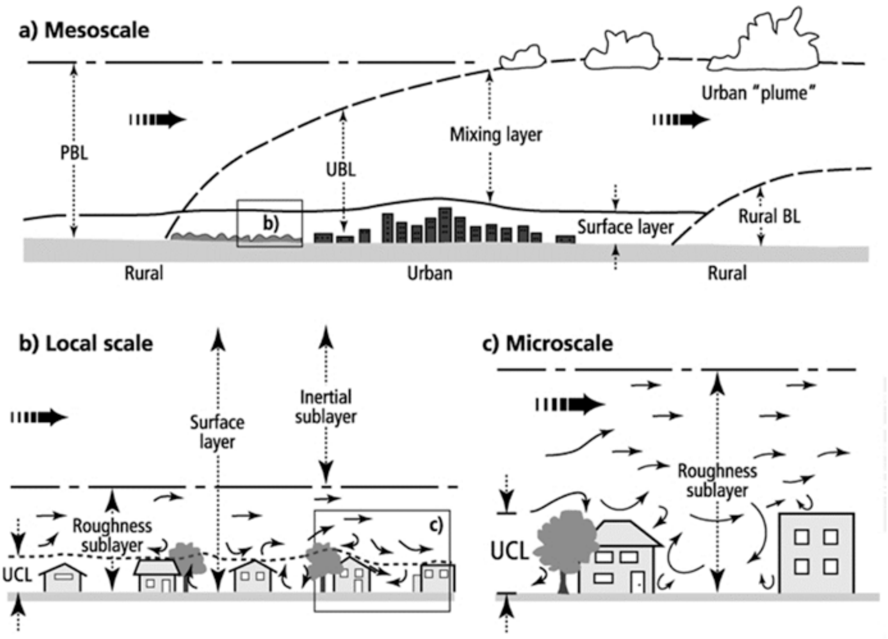


Fig. 7.2 Schematic of an urban boundary layer, UBL, within the planetary boundary layer (PBL). UBL sublayers and the (**a**) meso, (**b**) local, and (**c**) micro of Table 7.1 are also shown. From [28]

surface in urban areas is more variable than in closed natural forests, and the urban canopy layer is usually considered to be the entire space from the tops of trees or buildings, depending upon which dominates, down to ground level.

Within the roughness sublayer (Figs. 7.2 and 7.3), trees and buildings are dominant in creating the structure of turbulent wind flow and energy exchange; here eddies around individual buildings or trees (roughness elements) would be in evidence to sensors placed there. Above the RSL is the inertial sublayer where the influences of individual roughness elements have blended together so that although the friction with those elements is still present in affecting mean wind speed and the turbulent structure of the atmosphere, the effect of individual elements is no longer apparent. The RSL and the inertial sublayer together make up the surface layer where wind speed and turbulence, temperature, and humidity fluctuate greatly. Above the surface layer, these variables are nearly uniform with height.

The buoyancy and resulting amount of mixing within the PBL sublayer greatly influence the vertical air temperature profile and the hour to hour magnitude of UHI's. The buoyancy and mixing are described in terms of atmospheric stability. Mixing is strong during days with clear skies and light regional wind speed, and under these conditions, we say the PBL is *unstable*. During the night, if the sky is clear, radiative cooling lowers the temperature of the surface, the air just above the surface tends toward slow laminar flow, and the atmosphere is *stable*. With overcast sky or strong regional winds, or especially when both are present, temperature

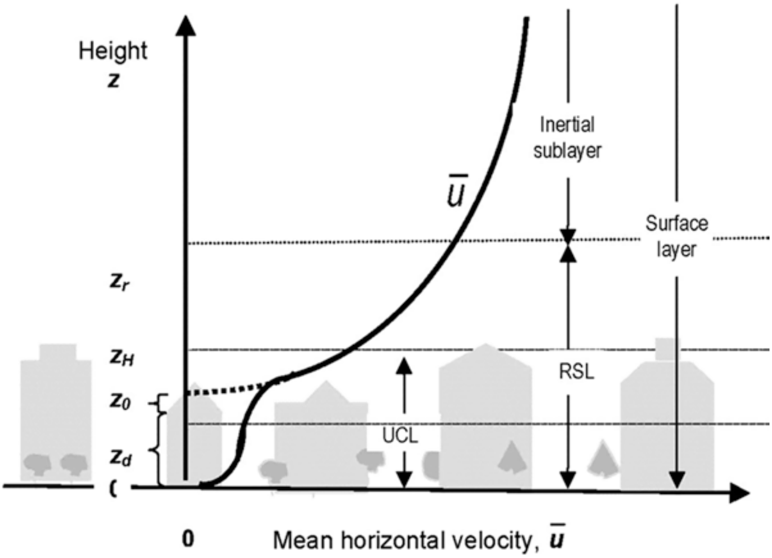


Fig. 7.3 Sublayers within the Earth's atmospheric surface layer in an urban area and a generalized mean vertical wind velocity ($\bar{u}$) profile. The measures on the height scale are the mean height of the roughness elements ($\underline{zH}$); the roughness sublayer (z_r and RSL); the zero-plane displacement (z_d) which is about 2/3 of z_H; and the roughness length (z_0), which is the height above z_d at which the above canopy wind profile extrapolates to 0 [30]

differs little with elevation, and we call this stability condition *neutral*. With strong wind speeds, there is much mixing of air in the surface layer, but it is mechanical, caused by turbulence from flow around trees and buildings, rather than thermal.

The mean horizontal wind speed, $\bar{u}$, within and above a relatively uniform UCL is depicted in Fig. 7.3. Starting near the top of the surface layer, $\bar{u}$ slows more and more as the top of the UCL is approached. The dotted line represents the extrapolation of the curve of wind speed, $\bar{u}$, to a theoretical zero near the top of the UCL at a height $z_o + z_d$. The roughness length, z_o, is aptly named because it defines the irregularity of a surface; z_o will be large for an urban area and very small for a relatively smooth surface such as a short agricultural crop. The shape of the $\bar{u}$ profile is influenced by the vertical motion contained in turbulent eddies generated by thermal and mechanical forces at the surface. These forces are carried upward on the eddies, which also mix the constituents of the atmosphere, including air pollutants, throughout the surface layer. The greater the turbulence-generating forces, the greater will be the mixing. Thus, mixing is greatest during unstable conditions and least under stable conditions.

Box 7.1: Indices of Atmospheric Stability

Atmospheric stability is critical not only to evaluating UHI effects but to evaluating dispersion of air pollutants. The state of this stability as it varies from

continued

Box 7.1 (continued)
day to night and with cloudiness and regional wind speed may be described by indices calculated from airport wind and cloud observations and elevation of the sun. One such index, the Turner Class, ranges from 1 for extremely unstable (little cloud cover, low wind speed near midday), to 4 for neutral (overcast sky or at least moderate wind speed or both), to 7 for very stable (clear sky, light wind at night) with values of 2, 3, 5, and 6 for intermediate conditions [21, 31].

Turner Class index has been shown to be a useful indicator of urban heat island intensity [21]. The conditions for a very stable atmosphere are also conditions that promote large UHI intensity. In Baltimore, MD, temperature differences between the city center and less developed points were usually larger with strong stability at night (Turner Classes 6 and 7)—see Sect. 7.6.4.

7.4.2 Topographic Influences on Urban Climate

Many cities are located in regions of considerable topographic variability. The terrain causes differences in local heating and cooling from place to place due to slope and exposure. Generally, heating of slopes and upper portions of valleys early in the day promotes local upslope and upvalley flow of warmer air, while after sundown a cooling of upper slopes and upvalley locales develops the impetus for downslope and downvalley cool air flow at night. Under relatively clear, calm weather, this local heating and cooling promotes thermally driven winds that vary in magnitude and direction during a diurnal period, much like a sea breeze system. Topographically generated air movement may have a large influence on temperature distribution, even in the small-scale topographic features of the East. Under stable atmospheric conditions (especially Turner Class 7, see Box 7.1), the relatively cool, heavy air near the ground moves by gravity downhill from higher elevations toward lower elevations. In some cities, this leads to effects on air temperature that may exceed the effects of land cover differences [21, 32, 33].

7.4.3 Measurements of Atmospheric Variables in Urban Areas

Routine air temperature measurements are often inaccurate because radiation, especially solar radiation, may cause large errors. In measurements for research and forecasting, temperature sensors are nearly always protected by shields to protect the sensors from radiation. However, unless the shields are aspirated by a fan, there will be significant errors during periods of full sun, sometimes of up to 5 °C or even more—errors that are significant in evaluating urban influences.

A cause of confusion about temperature differences is in the location of weather stations relative to ground cover and nearby obstacles. When the objective is to capture local scale or larger climate differences, temperature sensors should not be located close to buildings or near impervious ground cover, as is often done [34]. Confusion also results from station relocation, such as happened in Baltimore, Maryland, when the main city National Weather Service station was moved in May 1999 from the roof of a four-story building to a lawn near the water of the Inner Harbor. Loss of information about long-term temperature trends also results when stations are discontinued, such as happened to the Woodstock, Maryland, cooperative station, which was maintained for nearly a century until the 1990s.

To gain understanding of processes that create climate differences in urban areas, energy budget flux densities (as shown in Fig. 7.1) are often observed from tall towers (Box 7.2). Similar methods are used to measure fluxes of carbon dioxide (CO_2) to and from urban areas. Human-caused CO_2 emissions come from traffic, industrial processes, and heating and cooling of buildings. These sources of CO_2 are a concern for their contributions to global climate change.

Box 7.2: Measurements from Tall Towers

Observations of urban energy budget flux densities from tall towers generally use the *eddy correlation* (often referred to as eddy covariance) method. Vertical transfer of heat and moisture in the atmosphere is significant when the atmosphere is turbulent, that is, when eddies in the wind carry heat and moisture up or down. Eddy correlation measures the up or down transfer of heat by using fast response temperature sensors that measure the instantaneous temperature and vertical wind speed differences from their means over a sampling period of about 30 min. The system makes multiple measurements each second, and computer processing calculates the correlation between vertical wind and temperature differences for determining heat flux, Q_H, and similarly between vertical wind and humidity for latent heat flux, Q_E.

To be accurate, these measurements must be made in the inertial sublayer above the roughness layer (Figs. 7.2 and 7.3), so that the measurements are not influenced by flow over individual surface elements. This generally requires that sensors be placed at least twice the height of the tallest buildings or trees, which generally excludes measurements over areas of “skyscraper” buildings. Also, because of the considerable effort and cost to operate a tower facility, there is seldom replication of the measurements for a particular land use in a city. The area sampled by an urban flux tower is usually up to about 2 km in radius, that is, at the local scale (see Table 7.1).

Researchers also make measurements of carbon dioxide (CO_2) from towers by eddy correlation. For example, measurements in a Baltimore, MD, suburb showed that while the area was a net source of CO_2 on an annual basis, the large amount of urban forest vegetation in the suburb created net uptake of CO_2 from the atmosphere during summer daytime hours [35]. Urban areas with little vegetation are net sources of CO_2 at all times.

7.5 Types of Urban Heat Islands

Because the magnitude and timing of the different types of urban heat islands and how they relate to urban built and vegetative structure differ greatly, it is important to distinguish between the different types (Table 7.3).

7.5.1 Urban Canopy Layer Heat Islands

In UHI studies, canopy layer air temperatures are usually measured at about the height of people or the lower stories of buildings, between 1.5 and 3 m above ground. If that temperature is warmer than the temperature at the same height in nearby rural areas, then this is termed an UCL heat island [37, 38]. This chapter focuses on urban canopy layer heat islands.

7.5.2 Urban Boundary Layer Heat Islands

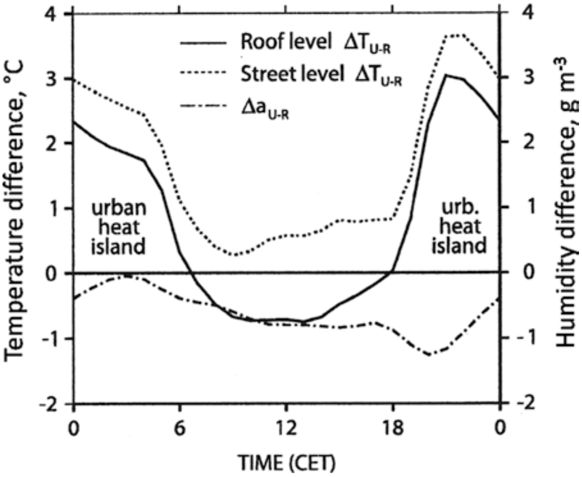
The heat island that forms in the atmospheric boundary layer above the city is the urban boundary layer (UBL) heat island [29, 38]. As we have seen in Sect. 7.4.1, the UBL varies greatly in thickness and turbulence over the course of a clear day, and thus the UHI in the UBL also varies. During the night, if the sky is not heavily overcast, the UBL is only a shallow layer. During clear days, the mixed layer expands vertically. This process increases UBL thickness to 1 km or more [39]. Boundary layer heat islands are most often studied by using computer modeling at the mesoscale. A commonly noted feature in the modeling results is a plume extending downwind of a city [40].

A comparison of urban minus rural air temperature differences (Fig. 7.4) associated with the energy budget measurements in Fig. 7.1 suggests the difference between UCL and UBL heat islands. The graph shows hourly street-level urban-rural temperature differences, averaged over 30 days in midsummer, from measure-

Table 7.3 Simple classification scheme of urban heat island types [36]

UHI type	Location
Air temperature UHI	
Urban canopy layer heat island	Found beneath roof or treetop level
Urban boundary layer	Found above roof level; can be advected downwind with the urban plume
Surface temperature UHI	Different heat islands according to the definition of surface used (e.g., bird's eye view 2D vs. true 3D surface vs. ground)
Sub surface UHI	Found in the ground beneath the surface

Fig. 7.4 Average urban-rural differences in air temperature (ΔT_{U-R}) at street level and above roof level, along with urban-rural absolute humidity differences (Δa_{U-R}) at sites where energy budget terms were measured above the urban and rural canopies as pictured in Fig. 7.1 [27]



ments at about 2.5 m above ground. It also shows the difference between temperatures at 5 m above the roofs (roof level) in a neighborhood of 10 m tall buildings compared to near ground-level rural temperatures. Both curves of ΔT_{U-R} show larger values at night, indicating the UHI effect. However, street-level ΔT_{U-R} UHI is larger and remains positive for all hours. Above roof level, ΔT_{U-R} is negative in midday because the vertical mixing in those hours brings relatively cool air from higher in the UBL down to the above roof level. Over all hours, the humidity difference, Δa_{U-R} in Fig. 7.4, was negative, which indicates greater humidity in rural areas. This is the result of greater evaporation in the rural agricultural area compared to the urban area with limited vegetation and available exposed soil.

7.5.3 *Surface Urban Heat Islands (SUHI)*

Urban heat islands may also be described by the temperatures of the upper surfaces of buildings, trees, streets, lawns, and so forth, as seen from above. This is sometimes called the urban "skin" temperature. This type of heat island should not be confused with "surface temperatures" as used in some climatology reports to refer to air temperatures near the ground, usually at a height of 1.5 m. The 1.5 m height is essentially *at* the surface of the Earth compared to the elevations at which temperatures are measured in atmospheric soundings (balloon measurements through the atmosphere), which may go to 30 km above the Earth. During the day, temperatures *of* the surfaces ("skin" temperatures) of nonliving solid material can be much warmer than air temperatures [41]. Temperatures of entire urban surfaces are generally measured by satellite [42]. With clear skies, upper surface heat islands are small at night and large during the day, the opposite of UCL air temperature heat islands [43].

Images of warm urban compared to rural skin temperatures as derived remotely from airplanes or satellites are commonly used as dramatic images of an UHI for the purposes of illustrating benefits of urban trees (e.g., [44]). Temperatures of trees and forests are usually not much above air temperature, and they can be shown in green in sharp contrast to a dark red for the commonly much warmer temperatures of building roofs and impervious asphalt surfaces. A benefit of such depictions is that the images show temperatures in a spatial continuum over a large area. However, the temperatures may be inaccurate because of the problem of correcting for absorption of thermal radiation through the atmosphere and for errors in apparent temperatures of surfaces that are not almost directly below the airplane or satellite and because the average emissivity ε of a large portion of a city is difficult to estimate.

7.5.4 Subsurface Urban Heat Islands

Though subsurface or soil urban heat islands have received less attention in research than air temperature or skin surface heat islands, soil temperatures are ecologically important. Soil temperatures control ecosystem processes such as release of CO_2 by respiration of fine-plant roots and soil microbes, nutrient cycling, nitrogen availability, and evaporation of water, which affects soil moisture. These multiple influences affect plant growth indirectly, and there are also direct effects of temperature on plant growth and storage of C in the soil [45]. Soil temperature also affects temperature of stormwater runoff, especially from impervious surfaces, and therefore stream temperatures are influenced (see Chap. 6) [46].

Very small-scale effects of surface cover or shading may affect near-surface soil temperatures much more than the UCL and UBL heat islands. Most studies of urban soil temperatures have concentrated on the effects of asphalt cover on temperatures of adjacent soil or of soil below the asphalt [25, 26]. However, a study in Baltimore, MD, analyzed average daily soil temperature at a 10 cm depth under turf grass and forest cover. Temperature was higher in urban than rural sites (15.0 °C vs. 13.5 °C) on an annual basis. Because of the moderating effects of forest cover, temperature differences were smaller in both urban forests[7] and rural forests than under turf grass, with annual averages being 12.6 °C for urban forest areas compared to 12.2 °C for rural forest areas [47].

7.6 Urban Heat Island Examples

Here we present some examples of UHI study results; some chosen from studies we have carried out. Other examples represent a range of methodologies. Most are studies of atmospheric UHI in the UCL. We justify presentation according to study

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[7] Here "urban forest" refers to groups of closely spaced trees, such as wooded portions of parks within the city.

method because the method determines the spatial and temporal coverage of the conclusions.

7.6.1 Short-Term Temperature Measurements: Fixed Locations

Measurements near Baltimore, MD [48], illustrated the influence of land cover and land use on temperature differences (Fig. 7.5). Temperatures were measured at six suburban sites: a grassy area near a large apartment complex (apartments, Fig. 7.5a, c), a residential area with heavy tree cover but few buildings (residential under trees), a residential area with some trees and large lawn areas (residential open), a woodlot (wood), a large open pasture (rural open), and at the Baltimore/Washington International Airport (airport). The urban reference site was in downtown Baltimore (R in Fig. 7.5a); none of the suburban sites were far from some developed land uses (Fig. 7.5b). From May through September, average hourly temperature differences, ΔT, downtown site minus each of the other sites, were positive for all hours of the day. For most sites, ΔT through the day followed the usual UHI pattern of moist temperate climates—urban areas slightly warmer in midday, more rapid cooling of more rural areas after sunset leading to a maximum heat island in a few hours, and the cooler suburban areas heating more quickly after sunrise to approach the temperatures of urban areas that are heating more slowly. The wood site was coolest both day and night, and the other site with many trees, residential under trees, was similarly cool during the day. However, the residential under trees site was unusual in not cooling as much as other suburban sites at night, in part perhaps because of cold air drainage away from the site into a nearby valley (Fig. 7.5a, c).

7.6.2 Mobile Sampling

At least as early as the 1920s, mobile temperature sensing was used to study temperature differences across cities, and the method may be the one most used to derive urban heat island patterns [49–52]. Although usually limited in the number of days and time sampled, the mobile method offers a good way to sample across urban to rural gradients. Mobile transects are often used in combination with observations at fixed stations along the transect route and sometimes along with remote sensing to measure urban heat island patterns [53]. In Phoenix, AZ, automobile transects showed that during clear sky early mornings (beginning at 0500 h), industrial areas, which had the lowest vegetative cover, were warmest, commercial areas were just 1 °C cooler, residential and greenbelt were 3 °C cooler, and agricultural areas, which were irrigated, were 6 °C cooler. In summer afternoons, beginning at 1500 h, all land uses averaged within 2 °C of each other, with industrial being warmest and agriculture coolest [54].

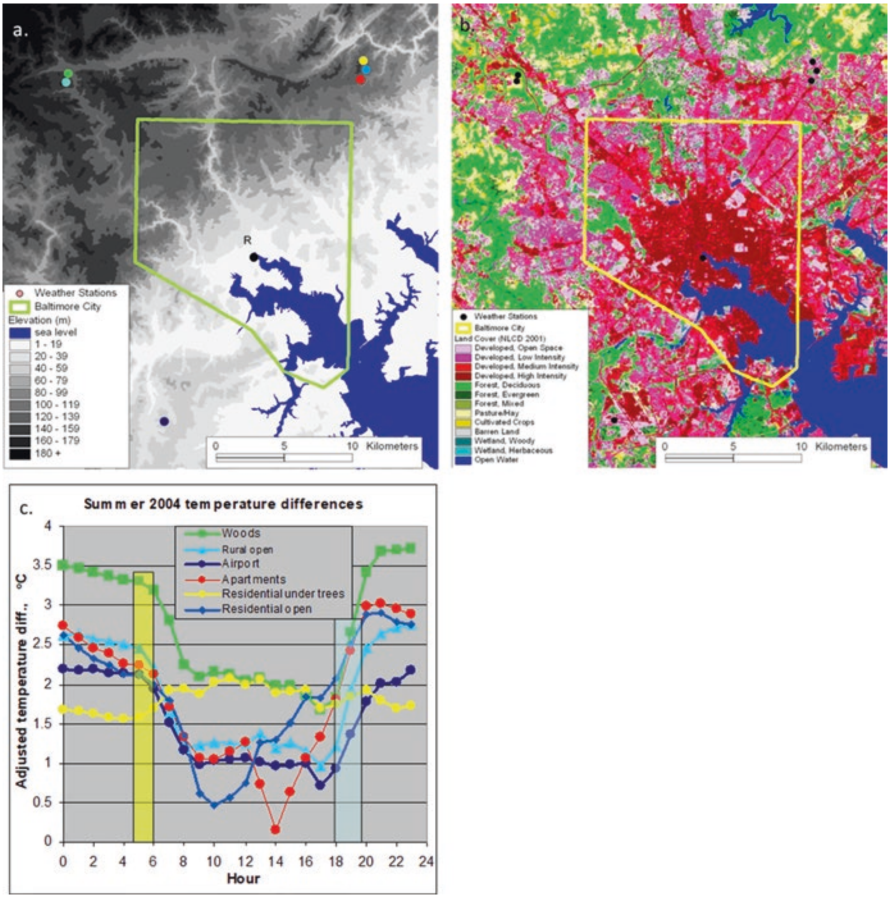

Fig. 7.5 (**a**) Elevation of Baltimore, MD, and vicinity with locations of 1.5-m-height temperature measuring sites color-coded to the average temperature differences in (**c**). (**b**) Land use for Baltimore and vicinity, with dark red being most developed, suburban residential mostly medium pink, developed open space such as parks light pink, agriculture yellow and brown, and forest green. (**c**) Differences in temperature, urban reference (*R*) minus other sites, averaged by hour of the day from May through September in different land-use categories. Temperatures adjusted for elevation difference. Range of times of sunrise and sunset indicated by shaded yellow and blue

In winter, the Phoenix measurements showed smaller temperature ranges: only 2 °C in the morning and only 1 °C in the afternoon. Measurements in some other cities have also shown smaller UHIs in winter, but others have shown winter UHIs to be greater than summer UHIs. It seems that the difference in magnitude of UHIs between summer and winter is sufficiently small that careful analysis is needed to assess which season has the most intense UHI. The difference between summer and winter UHIs depends largely upon the winter versus summer temperatures and solar radiation climate, which determine the amount of energy used for heating and cooling buildings.

In Puerto Rico, results from automobile measurements showed that the San Juan UHI has reached outward from the center of the city toward the east about 25 km [53]. In this case, the transect followed a main highway along which there was considerable recent development.

7.6.3 Analysis of Long-Term Records

Long-term temperature records can show the influence of urbanization, especially where temperature records are available from the start of development. A rare example of where this was possible was for Columbia, Maryland, where, in 1968, just after the start of the development, a heat island effect of 1 °C was observed in a small residential area, and a 3 °C heat island was found in a large parking lot. Six years later, the population had reached 20,000, and the maximum UHI had increased to 7 °C [1].

Analysis of historical data (GHCN, see Box 7.3) provided a comparison of UHI trends during the twentieth century for Baltimore, MD, and Phoenix, AZ [23]. The useable climate records began as early as 1908 and extended to 1997 for some stations. For the Baltimore region, the analysis used average daily maximum and minimum temperatures for July. For Phoenix, data were from May. Time series of the urban-minus-rural temperatures ($\Delta T\mathrm{max}_{U-R}$) at the time of the daily maximum temperature showed a difference between the humid, forested Baltimore compared to the arid desert Phoenix. In Baltimore, urban maximums are usually warmer than rural, whereas in the Phoenix area, urban maximum temperatures tend to be cooler than rural maximums (Fig. 7.6a, b). That is, values of $\Delta T\mathrm{max}_{U-R}$, which occur in daytime, tend to be negative in Phoenix, making an urban cool island. We believe this results partly from extensive watering of plants in urban areas, though the high rate of warming at the rural desert reference stations may be another part of the cause [55]. In both Baltimore and Phoenix, there are only slight long-term trends of changing $\Delta T\mathrm{max}_{U-R}$. Thus, evaluation of a city's overall UHI requires inclusion of nighttime observation.

Box 7.3: Historical Climate Data (GHCN)

One source of long-term records is the Global Historical Climate Network (GHCN) maintained by the National Centers for Environmental Information (NCEI) of the US National Oceanic and Atmospheric Administration (NOAA). The GHCN databases are available for public access online (search GHCN). The databases include quality-assured daily and monthly climate summaries from land surface stations across the Earth. For some stations many variables are provided, including temperature, total daily precipitation, snowfall, and snow depth; however, about two-thirds of the stations report just precipitation. Length of records varies from station to station, but for some, data extend to over 175 years.

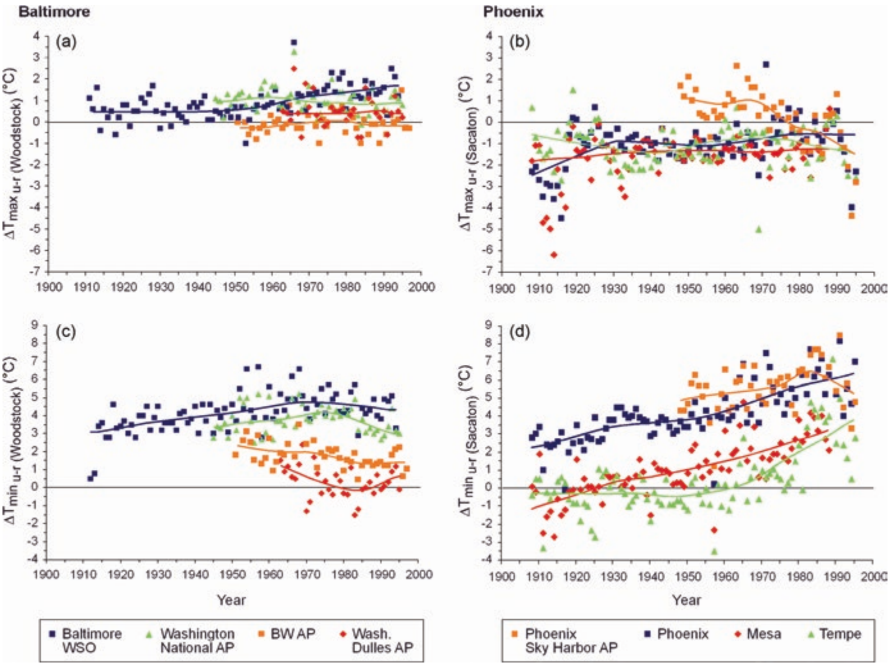

Fig. 7.6 (**a**) Long-term July monthly averages of maximum daily urban temperature minus corresponding rural temperatures (at Woodstock, MD about 24 km west of Baltimore) for stations in and near Baltimore. (**b**) May monthly maximum daily urban temperature minus rural temperatures (at Sacaton, AZ south of Phoenix) for the Phoenix region, and (**c**) and (**d**) monthly averages of minimum daily urban temperatures minus corresponding rural temperatures. From Brazel et al. [23]

There were definite long-term trends in urban-minus-rural temperature ($\Delta T\text{min}_{U-R}$) at the time of the daily minimum temperature (Fig. 7.6c, d). The $\Delta T\text{min}_{U-R}$ values tend to reflect population trends in the two cities. In Baltimore, $\Delta T\text{min}_{U-R}$ peaked at 4.5 °C in 1970, and decreased slightly after that, apparently because of population declines within the city and development encroaching on the rural site. In Phoenix, $\Delta T\text{min}_{U-R}$ increased substantially from about 2.5 °C in 1908, when population was only a few thousand to 6.5 °C in 1995 when population was about 700,000. As is typical of most cities, the UHI increase with population was rapid in early years of development and then increased at a slower rate as the city grew large. The rural comparison site for Phoenix, Sacaton, developed little during the twentieth century.

Thus, as has been found in many other cities, the UHI in both Baltimore and Phoenix is primarily manifested in increased nighttime temperatures rather than in greatly increased temperatures during the warmest part of the day. Many other cities show a long-term warming trend that can be attributed to both increasing urban heat island effect as population increases and to global climate change (see Sect. 7.10).

Another pertinent comparison of the heat island in different cities is the maximum intensity of the urban heat island, $\Delta T_{U-R(\text{max})}$, which is similar to $\Delta T\text{min}_{U-R}$, which usually occurs at night. Average $\Delta T_{U-R(\max)}$ has been found to vary with population [56] as we saw for $\Delta T\min_{U-R}$ in Baltimore and Phoenix. Because of the different typical city structure, $\Delta T_{U-R(\max)}$ is usually greater in the United States than in European cities of equal population. Tropical and subtropical cities have generally smaller $\Delta T_{U-R(\max)}$ values than higher-latitude cities [57]. Also, $\Delta T_{U-R(\max)}$ tends to be lower in wet than dry climate tropical and subtropical cities.

7.6.4 Empirical Modeling

To evaluate the influence of urban cover on UCL air temperatures, especially the influence of urban trees on temperature, a study of Baltimore, MD, used regression analysis with high-resolution (10 m) remotely sensed tree and impervious cover data along with hourly weather data to develop relationships for predicting temperature differences (ΔT) between the reference site (indicated by "R" in Fig. 7.5a) in central Baltimore and the six other weather stations in different land uses around the city [21]. One predictor of ΔT was the difference in upwind land cover between stations. Land cover had an influence on air temperature, but there were strong interactions between land cover and other predictors of ΔT, particularly atmospheric stability and topography. Land cover differences out to 5 km in the upwind direction were significantly related to ΔT under stable atmospheric conditions (Turner Class stability index, see Box 7.1, was a useful indicator of urban heat island intensity).

The regression equations combined with recent GIS tools [58] permitted mapping ΔT across a mesoscale-sized area of Baltimore and surroundings (Fig. 7.7). The GIS methods have the potential for testing the effects on temperature of changed land cover, for example, by inputting and mapping different scenarios of altered tree or impervious cover. Figure 7.7a is for midafternoon of a partly cloudy summer day with low wind speeds, which created moderately unstable conditions (Turner Class 2, see Box 7.1). The coolest point is 4.1 °C cooler than the warmest. But more than half of the predicted temperature difference is due to differences in elevation. With the elevation factor removed from the ΔT prediction equation (Fig. 7.7b), the influences of land cover alone are illustrated for the same time as in Fig. 7.7a; land cover causes a ΔT range of about 1.6 °C. In Fig. 7.7c, with clear sky and low wind speed at night (Turner Class 7, very stable), the UHI effect is near maximum. A large city park (Patterson) is about 2 °C cooler than the dense residential area surrounding it. The patterns of elevation and land use are evident in the pattern of predicted ΔT in Fig. 7.7c.

7.6.5 Mesoscale Meteorological Models

Mesoscale meteorology models are used to carry out numerical simulations of atmospheric conditions over three-dimensional atmospheric space with horizontal extent of up to thousands of kilometers and vertical extent of the entire lower

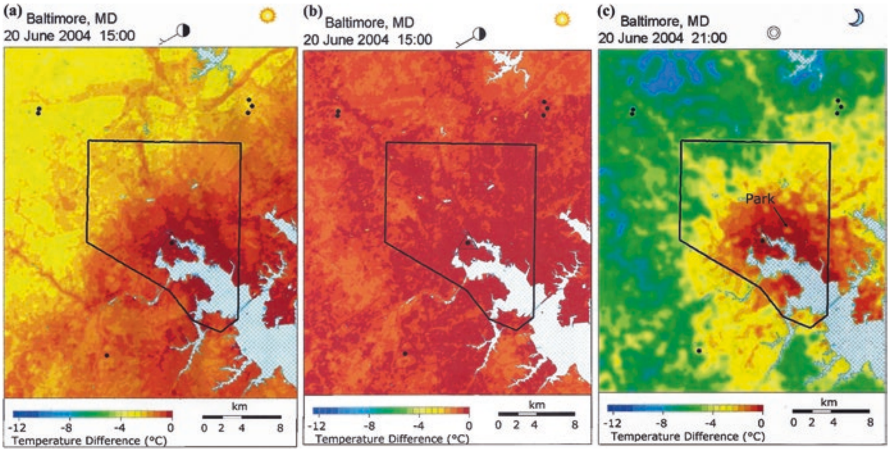

Fig. 7.7 (**a**) Modeled air temperature differences (Δ*T*) at 1.5-m-height across Baltimore, (black line) and vicinity. Black dots indicate weather stations. This map is for 1500 local standard time of a partly cloudy summer day with low wind speeds (<2.6 m/s = 5 kt), Turner stability Class 2. Water shown by cross-hatched blue. Solid colors indicate Δ*T* with respect to the warmest temperature on the map (dark red). The coolest point (light yellow) is 4.1 °C cooler. (**b**) With the elevation factor removed from the Δ*T* equation, the influences of land cover are illustrated for the same time as in (**a**); land cover causes a Δ*T* range of about 1.6 °C. (**c**) With clear sky and low wind speed at night, Turner Class 7, the UHI effect is near maximum. A large city park (Patterson) is about 2 °C cooler than the dense residential area surrounding it. See Fig. 7.8a for elevation map of the Baltimore area and Fig. 7.8b for land use

atmosphere. They are used in a wide range of studies and disciplines, such as weather prediction, hydrologic modeling, air chemistry, atmospheric dispersion, regional and climate assessments, and urban climate. The models simulate meteorological conditions, such as wind, temperature, and vertical mixing. They may be used for predicting air temperature near the ground (2 m in height), wind speed and direction at 10 m above ground (the international standard height for wind measurements), and air quality, including ozone and fine particle concentrations.

Mesoscale model development has been underway for more than three decades and has progressed as computer capabilities have progressed to be able to carry out the solutions of huge numbers of primitive (based on first principles) equations that begin with those describing the conservation of mass, heat, and motion [60]. Mesoscale modeling today most often uses the Weather Research and Forecasting (WRF) model, a numerical weather prediction system that serves both forecasting and atmospheric research needs. Mesoscale models couple the ground surface to the atmosphere, and they require ground cover conditions as input. Varying horizontal scales may be used; for modeling city-scale processes, the grid spacing is less than with synoptic scale models, but still large, typically about 2 km, though in some cases as small as 0.5 km [61].

A mesoscale study with 0.5 km resolution evaluated the afternoon UHI in the Baltimore-to-Washington metropolitan area [62]. The UHI patterns for Baltimore derived by the mesoscale modeling were similar in general form to the UHI pattern using the empirical method described in Sect. 7.6.4; and the magnitudes of the UHI were similar, 4–5 °C, by both methods. The 10 m resolution of the empirical data produced much more detail in the UHI pattern, detail that would be useful for planning UHI mitigation such as by tree planting [21]. The mesoscale maps covered not just Baltimore and near vicinity but also the entire area from Baltimore to Washington. This led to the conclusion that the PBL plume from Washington, DC, may have enhanced the magnitude of the UHI in Baltimore UCL by 1.25 °C [62].

7.7 Urban Wind

Modifications to wind flow by buildings and trees strongly interact with air temperature, radiation balances, and heat storage terms to affect urban climate, human comfort and health, and energy use in buildings. Although our emphasis in this chapter is on urban structure influences on air temperature, the environmental influence of trees and buildings on wind speed and turbulence will often be greater than influences on temperature.

7.7.1 Effects of Trees and Buildings on Wind

A study in relatively low-building-density residential neighborhoods in Pennsylvania measured wind speed at the 2 m height in four neighborhoods of single-family detached houses that were selected for their similar housing stock and different tree cover [63]. The mostly deciduous tree cover ranged from near 0% to 77%, and building footprints within the neighborhoods ranged from 6% to 12% of the area. Measurements at houses were adjusted for the effect of the houses at which the measurements were made. That is, the purpose of the study was to determine the effective wind force on individual houses, but when wind speed is measured just upwind of a building, the building itself will reduce wind speed; the adjustment increased apparent wind speed accordingly. Apparent wind reductions by other houses throughout the neighborhoods ranged from 21% to 24%, and by trees from 28% to 46% in summer and 14% to 41% in winter (Fig. 7.8). Thus, with the loss of leaves in winter, wind reductions by trees were 50% less in the low-tree-density neighborhood, but only 5% and 11% less in the neighborhoods with greater tree cover.

In the Pennsylvania analysis, average wind speed reduction in summer as a percentage, U_r, was approximately related to the sum of tree canopy and building footprint cover as a percentage, $C_{b,t}$, by

$$U_r = 100C_{b,t} / \left(24 + 1.1C_{b,t}\right). \tag{7.6}$$

When tree and building cover are relatively low, a small increase in density has a large effect in reducing wind speed (Fig. 7.9).

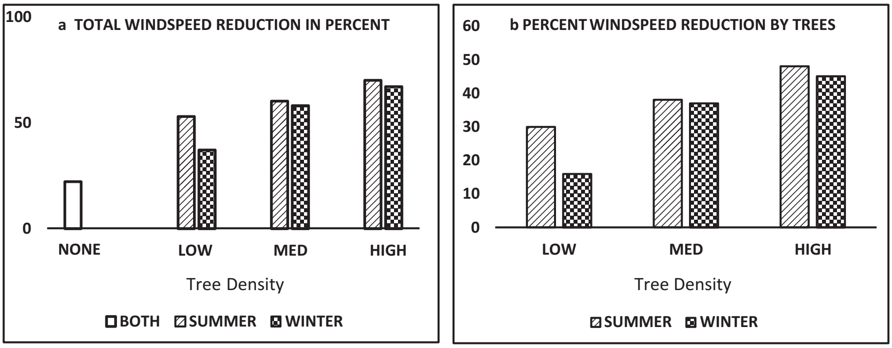

Fig. 7.8 (**a**) Mean wind speed reductions and (**b**) apparent reductions by trees in four neighborhoods, with different tree density [63]

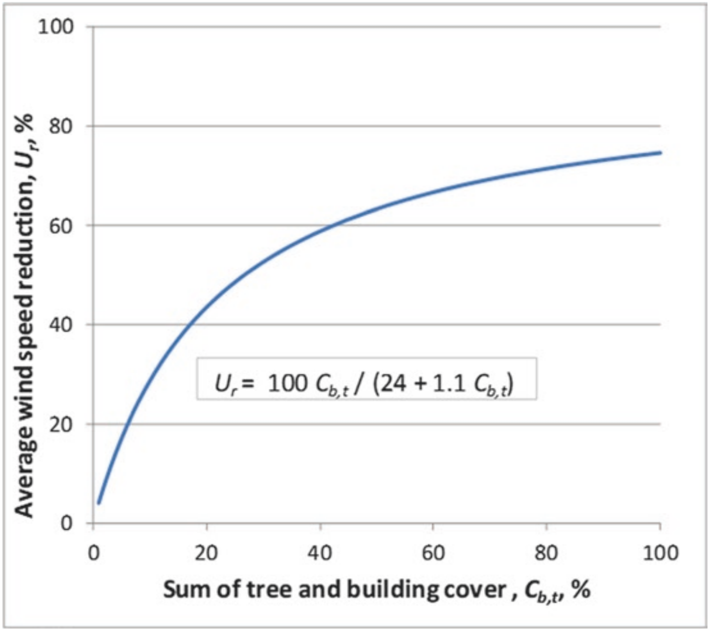

Fig. 7.9 Average wind speed reduction in summer by trees and buildings in neighborhoods of single-family detached houses in Central Pennsylvania [63]

Tall buildings in cities, especially where some skyscraper-type buildings are much taller than others, create complex flow at ground level. Wind perpendicular and at a high elevation on a tall building wall may be directed down the face of the building and then accelerated around the corners of the building. Near pedestrian level, wind may be increased to two or three times the speed of wind in an area with no buildings [64]. On the downwind side of tall buildings, there tends to be an area of reduced wind speed, but direction may be opposite to that of the undisturbed flow.

In an area of Dayton, Ohio, with scattered tall buildings, wind speed increased with height of the nearest upwind building and decreased with distance from the building, evidently an effect of acceleration around the corners of buildings [65]. The measurements in Dayton were carried out with regional thermal stability ranging from neutral to moderately unstable. Relative wind speed (wind in city/wind at airport) increased with decreasing stability. Unstable conditions increase turbulence in wind flow. The decreasing effect of obstacles to reduce mean wind speed as stability decreases is similar to the effect observed in many studies of tree-row windbreaks that show reduced effectiveness with increased turbulence of the wind approaching the windbreak [66]. Even in the Dayton central business district, street trees significantly decreased wind speed [67].

7.7.2 UHI-Driven Air Flow

A city will generate its own local country-to-city wind regime due to the heat island effect when regional winds are very light [8]. Warm, unstable air in the city rises, creating a low-pressure area that induces air to move from the country to converge and rise in the city center. When regional winds are exceptionally low, the city thermal winds may exceed wind speed in the country [68].

The UHI effect may also impact more regional topographically induced thermal wind systems. The center of Phoenix, AZ, lies on a relative flat area with a long gradual slope up toward mountains on the northeast. Mesoscale modeling showed that during the afternoon, regional winds tend to blow upslope and up smaller valleys toward the mountains. At night, there tends to be cool air drainage downslope toward the city. The modeling showed that (a) between 1973 and 2005, local winds in the city area were increasingly slowed by the rapid growth of the city and (b) the urban area slowed the upslope winds flowing away from the city to the north and east during the day [61]. Thus, not only did the urban area impact overall wind speed but also imposed differential effects on the prevailing topographic thermally driven wind system.

7.7.3 Sea Breeze in Cities

Cities located on coasts of large lakes and near oceans experience yet another diurnal wind system that we know as the sea breeze (land breeze at night). This phenomenon is driven again by differential heating, in this case of land and water, with the result of onshore flow during the day (cooler air off the water toward the heated land) and offshore flow at night. There are myriad examples in urban climate of the importance of these breezes for human comfort (especially for tropical cities), air quality, and the dimension of the UHI. Usually sea breezes bring cooler air from the water to seaside cities. This is the case with the massive UHI of the city of Tokyo that observations showed may be moderated by up to about 2 °C, with some cooling extending for at least 10 km into the city [69, 70].

In the case of Hong Kong, a large tropical city on hilly topography surrounded by irregular ocean coastline on three sides, ventilation by air movement at pedestrian height is a key factor in ameliorating the large UHI that develops in that city. Rather than creating ventilation that would reduce the UHI, the complex topography with up- or downslope winds and sea breeze combine under some synoptic wind flow conditions to produce air stagnation and dangerously high air pollution levels [71, 72]. Hong Kong has water on the east, west, and south. Under light synoptic winds from the north, the sea breezes from the other three directions converge to cause the air stagnation. The dense, total building landscape of Hong Kong exacerbates the lack of adequate ventilation. In some cases, large blocks are entirely covered by one building just a few stories tall, a "podium," upon which tall skyscrapers stand. A podium greatly reduces air movement at pedestrian height. Much effort has been expended for planning to incorporate ideas important for future design of the city [73].

7.8 Urban Effects on Precipitation

Much research has been carried out on the proposition that urban areas significantly affect precipitation [74]. Cities may affect precipitation in a variety of ways: by increasing *convection*[8] through the UHI effect, by high levels of pollutants that form *cloud condensation nuclei (CCN)*, and by the increase in roughness and upward forcing of air flow over areas of tall buildings [1]. Other possible urban influences on precipitation are diverting of storm systems around cities and by irrigated urban areas in dry climates serving as sources of moisture needed for convective development [74]. The small or negative daytime heat island in Phoenix, which exists because of irrigation, has consequences for urban convection effects on precipitation. The convection probably is greater just outside the urban core than within it. However, examination of long-term precipitation trends for the Phoenix area suggests a 12–14% increase of rainfall in the generally downwind direction from the city center [75].

METROMEX was a large multi-year research project with the primary goal of investigating the effects of St. Louis on precipitation [76]. Four years of research indicated that St. Louis increased summer rainfall downwind of the urban-industrial complex [77], and the increases amounted to as much as 45% [1]. The increase appeared to be caused by intensification of natural storm systems by a combination of the UHI and by addition of condensation nuclei from pollution. Lightning, which is caused by the vertical convection process, was also significantly increased in St. Louis, primarily downwind of the city center [78].

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[8] This convection consists of the vertical rise of air that has been heated and thus made buoyant by the urban area.

One reason that uncertainties remain about urban influences on precipitation is the considerable natural spatial variation of storm totals from point to point. Equally problematic is the difficulty of accurately measuring precipitation with rain gauges. The main types of errors are (1) those caused by positioning of the gauge so that precipitation is shielded from the opening of the gauge; (2) by wind diverting the rain and, especially, snow from the opening; and (3) errors of the measuring system within the gauge. Most commonly used rain gauges today are of the tipping bucket type, which have two small bins, or "buckets" that alternate catching the rain until full and then tip, dumping their catch and making an electrical contact to provide a count. Accurate measurement of precipitation is sufficiently important for water management in many cities around the world that researchers have expended considerable effort to derive methods to calibrate and correct rain gauge errors [79].

7.9 Influences of Parks

Parks in urban areas not only serve recreational functions but create their own microclimatic conditions, which especially for large cities in warm climates provide a cooling ecosystem service for the public. Although the prevailing idea is that parks cool an area [80], the magnitude and even the direction (+ or – relative to its surroundings) of the impact of a park on temperature within an urban area depend on a host of factors such as shape, size, composition (% trees, grass, water, impervious ground, and density of vegetation), and kind of land cover surrounding the park. Table 7.4 gives some examples of park nighttime cooling impacts, size of parks, and "extension" distances of cooling effects away from the park that have been detected. There appears to be no clear pattern to the park effects. Generally, it is assumed that bigger parks would affect larger surrounding areas, but this is not always the case, as the composition and roughness of surrounding areas partially dictate this impact. Another subtle effect is the tree canopy impacts at night. A heavily tree-covered park may be warmer than a park with large grass areas, because outgoing LW radiation to a cold night sky may be larger than in a tree-covered area [81]. Fig. 7.7c points to a large city park in Baltimore that empirical modeling predicted will be about 2 °C cooler than surrounding areas at 9:00 PM. There are seven other large parks in Baltimore that had easily recognized influences on temperature. The parks averaged 1.7 °C to 5.9 °C cooler than the warmest location in the city at 9:00 PM on a clear night with low wind speed [90].

7.10 Relationship to Global Climate Change

The UHI effect in even modest-sized cities is at times much larger than the approximately 1.0 °C of average global temperature warming above preindustrial levels estimated to have been caused by human activities by the Intergovernmental Panel on Climate Change [82]. This is true especially on clear nights with low wind

Table 7.4 Maximum temperature difference (Max. ΔT_{u-p} °C) from surrounding city and extent of park influences on temperature at a range of latitudes and climate types [80]

City	Latitude, °N	Climate	Park size (ha)	Max. ΔT_{u-p} °C	Extension (*m*)
Washington, DC	40	Humid subtropical	–	3–5	
Mexico City	20	Short grass prairie	525	6	2000
München	48	Humid continental	130	3.5	
			2.5	2.0	
Montreal	45	Humid continental	38	2.0	400
Kumamoto city	33	Humid continental	2.25	4	20
			0.24	3	15
Kuala Lumpur	3	Tropical rain forest	153	4.1	
			46	3.1	
			19	1.9	
			1.6	1.5	
Goteborg	57	Marine west coast	156	6	1500
Tucson	32	Hot dry desert	171	6.8	

speeds. Global warming is caused by accumulation of "greenhouse" gases (GHG) in the stratosphere, a completely different phenomenon than the processes that cause UHIs. However, global warming and UHI effects are linked because a large portion of the GHGs are produced in urban areas and the UHI effect modifies, either positively or negatively, the urban emissions of GHGs [5]. Positive UHI contributions to GHG come from increased energy use for air conditioning in summer. Negative contributions may come from reduced energy use for heating buildings in winter, though this effect is generally not considered. Perhaps more importantly, the UHI effect makes terrestrial air temperature monitoring of the global effect uncertain because for many weather stations it is difficult to separate UHI influences from the global influences [83, 84].

7.11 Mitigation of Urban Heat Islands

When considering the literature on the mitigation of urban heat islands, special attention should be paid to experimental design, assumptions of the study, and the language. Ask yourself if experimenters were without bias in designing the experiment and interpreting results, or whether they consciously or unconsciously set out to show the benefits of their method of heat island mitigation. When a research team is charged with the responsibility to propose UHI mitigation strategies, it is difficult to avoid being overly optimistic about possible effects of the proposed strategies.

Studies of UHI mitigation are most often limited in some way. Studies in temperate climates usually consider only summer and not winter. Thus, possible winter benefits of UHI are often not considered. The most common approaches to UHI reduction are increasing albedo of urban surfaces, or “whitening,” and large-scale tree planting [85]. A study to predict the effects on mitigation of the UHI of New York City if tree planting, white pavements and roofs, and green roofs were implemented used mesoscale modeling and satellite skin surface images to predict “near-surface” air temperatures [86]. The study concluded that all of the mitigation strategies could reduce summer UHIs, but the best was a combination of tree planting (on 17.5% of city area) and living roofs, which had the potential of reducing peak afternoon temperatures by 0.7 °C if fully implemented. Any possible negative influences by reductions of winter air temperature or increases in heating costs for buildings by tree shade were not considered, and possible net benefits of trees and living roofs in winter were also not considered.

Another mesoscale modeling study for a large city predicted that the Los Angeles, CA, heat island could be reduced by as much as 3 °C by “cooler” (lighter) roof and paving surfaces and the planting of 11 million more shade trees [87]. The most common application of whitening has been for roofs, though light-colored paving has also been recommended [88]. A similar study predicted that increasing the albedo of streets and of residential, commercial, and industrial areas in the Los Angeles basin from 0.139 to 0.155 would reduce predicted 1500 h air temperatures by 2 °C, which would cause a significant reduction in predicted ozone concentrations [89].

Another mitigation effect could be the use of irrigation of vegetation. In Phoenix, a small cool island exists during the day, apparently because of irrigation of vegetation in the city [23, 61]. In Los Angeles, the maximum air temperatures decreased during the city’s early development, as dry arid regions were replaced with irrigated orchards and farmland [88].

The US Environmental Protection Agency tried over many years to produce for planners and administrators a set of scientific explanations for UHI effects and guidelines for mitigation of UHIs on which most researchers in the field could generally agree. The current online version (as of 2008 and 2009) covers in separate documents: UHI basics, mitigation by trees and other vegetation, green (living) roofs, cool (light colored) roofs, cool pavements, and activism in the cause of UHI reduction including tree planting programs, ordinances, and building codes and zoning [90]. The US EPA has this and a wide range of other applied information on their website titled “Heat Island Effect.”

7.12 Conclusions

The feature of urban climate systems that is usually of most concern is that urban areas usually have warmer air temperatures than more rural areas, the urban heat island effect, UHI. The magnitude of the UHI generally increases with city size and population. The UHI is usually not more than 3 or 4 °C during midday. Depending upon the rural reference site and synoptic weather conditions, the UHI effect in large cities may range up to about 11 °C, usually within a few hours after sunset (see Sect. 7.6).

Comparisons of urban to nonurban climate are seldom made between urban conditions and those representative of conditions before development. The comparison is usually with agricultural areas, where the environment has already been drastically modified by humans. Dry, desert climates have maximum UHIs of similar magnitude to moist climates, unless the rural comparison is with unirrigated desert. In that case, during the daytime, the temperature island may turn out to be a small-magnitude cool island, in part because of evaporative cooling of irrigated vegetation within the city and because the dry desert becomes very warm owing to the low admittance of desert vegetation and soils (Sects. 7.3.3 and 7.6.3.).

Urban heat islands are caused by a combination of factors:

- The high thermal admittance (high thermal entropy) of urban building and infrastructure materials that lead to greater daytime storage and nighttime release of heat in urban than rural areas (Sect. 7.3.4)
- Less vegetation and availability of soil moisture in urban areas that lead to less evapotranspiration and a larger proportion of net radiation (commonly termed Q^* in climate literature) going into sensible heat flux (Q_H) than latent heat flux (Q_E) in urban areas (Sect. 7.3.3)
- Emissions of heat from buildings, transportation facilities, and industrial processes (Sect. 7.3.1)
- Greater air pollution and aerosols in urban areas, which usually leads to an increase in Q^* (Sect. 7.3.2)
- The effect of tall buildings in trapping thermal radiation within canyon-like building walls, thus effectively increasing the overall urban Q^* and reducing nighttime cooling by outgoing thermal radiation (Sect. 7.3.2)
- The effect of tall buildings in reducing mixing of near-surface air with cooler air at higher elevations (Sect. 7.7.1)

The UHI effect is usually considered to be detrimental. Warmer temperatures increase ozone production in urban atmospheres; increase use of energy for air conditioning, thereby increasing emissions of CO_2; and increase adverse effects on human health and mortality in heat waves. In temperate climates, UHIs are usually greater in summer than winter because of the greater amount of solar insolation in summer. However, substantial UHIs can also form in winter, with the benefits of reducing costs for heating buildings and less snow and ice hazard. The winter benefits of UHIs have seldom been quantified and compared to the detriments of summer (Sect. 7.11).

The most common approaches to UHI reduction are increasing vegetation cover and increasing albedo of urban surfaces, or "whitening." Urban whitening most often takes the form of making roof surfaces lighter so that solar radiation is reflected back to space, effectively reducing Q^* in the urban energy budget. Increasing vegetation includes "green roofs," which insulate roofs and increase evapotranspiration causing greater Q_E, and tree planting, which shades high thermal admittance surfaces and also increases Q_E (Sect. 7.11.)

Urban areas have effects on precipitation and wind that are partly the result of warming due to an UHI. The precipitation effect usually results in increases downwind of the city center. The UHI effect on wind generally occurs with very light synoptic winds when air rises over the warm city to cause low level flow into the city. Trees throughout residential areas with low building density may have dramatic effects on wind speed with reductions of over 40% even in winter where most trees are deciduous (Sects. 7.7 and 7.8).

Global climate change and the UHI effect are caused by completely different physical processes, the global change in temperature caused by changes in upper atmosphere constituents, and the UHI effect by land cover. However, the UHI effect makes air temperature monitoring of the long-term global climate change uncertain because many weather stations are influenced by urban influences (Sect. 7.10).

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Chapter 8
The Atmospheric System: Air Quality and Greenhouse Gases

David J. Nowak

Abstract Trees in cities affect air quality and greenhouse gases in numerous ways and consequently affect environmental quality and human health. Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmospheric environment. The main ways that urban trees affect air quality and greenhouse gases are through (a) air temperature reduction and other microclimatic effects, (b) removal of air pollutants and atmospheric carbon, (c) emission of volatile organic compounds and emissions associated with tree maintenance, and (d) altering energy use in buildings and consequently pollutant and carbon emissions from power plants. By understanding the effects of trees and forests on the atmospheric environment, managers can design appropriate and healthy vegetation structure in cities to improve air quality and consequently human health and well-being for current and future generations.

Keywords Pollution removal · Climate change · VOC emissions · Urban forests · Air temperature

8.1 Introduction

Trees in cities are a significant resource that affects the city atmosphere and consequently human health and environmental quality. Trees affect the atmosphere in numerous and interactive ways. This chapter will focus on the chemical constituents of the atmosphere related to air quality and greenhouse gases but will draw upon other atmospheric effects related to meteorology that are described elsewhere in this book. Trees significantly influence the local atmospheric environment through the

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exchange of gases and alteration of wind and solar radiation within the city. These influences are due mainly to the evaporation of water from tree leaves (transpiration), exchange of gases at the leaf surface, and the physical mass of the plants' woody and leafy tissue that can intercept materials and energy and alter wind patterns. Trees affect the urban atmosphere primarily by regulating air temperature (see Chap. 7) and altering air pollution and atmospheric carbon dioxide fluxes and concentrations. The purpose of this chapter is to provide a better understanding of how urban forests affect air quality and greenhouse gases.

8.2 Air Quality

Air pollution significantly affects human and ecosystem health [1]. Recent research indicates that global deaths directly or indirectly attributable to ambient air pollution reached almost 4.5 million in 2015 [2]. Air pollution is the largest environmental cause of disease and premature death in the world [3], with the World Health Organization [4] stating that air pollution is the largest environmental risk factor.

Ambient air pollution caused 107.2 million disability adjusted life years (number of years lost due to ill-health, disability, or early death) in 2015 [2]. Human health problems from air pollution include aggravation of respiratory and cardiovascular diseases, increased frequency and severity of respiratory symptoms (e.g., difficulty breathing and coughing, chronic obstructive pulmonary disease (COPD), and asthma), and increased susceptibility to respiratory infections, lung cancer, and premature death [5–7]. Worldwide, there are an estimated 300 million people with asthma and 210 million people affected by COPD [8]. Recent studies also suggest that air pollution can contribute to cognitive and mental disorders [9–11]. People with pre-existing conditions (e.g., heart disease, asthma, emphysema), diabetes, and older adults and children are at greater risk for air pollution-related health effects. In the United States, approximately 130,000 deaths were related to particulate matter <2.5 μm ($PM_{2.5}$) and 4700 deaths to ozone (O_3) in 2005 [12].

Between 1990 and 2016, air quality in the United States has improved for the six common air pollutants, with lead (Pb) concentrations improving by 99%, sulfur dioxide (SO_2) by 85%, carbon monoxide (CO) by 77%, nitrogen dioxide (NO_2) by 50%, particulate matter <10 μm (PM_{10}) by 39%, and ozone (O_3) by 22%. In addition, particulate matter <2.5 μm ($PM_{2.5}$) has improved by 44% since 2000 [13]. Despite these improvements in air quality, approximately 107 million people live in areas of the U.S. that exceeded the national ambient air quality standards (NAAQS) for ozone in 2017, 23 million for $PM_{2.5}$ and three million for SO_2 [14].

In addition to affecting human health, air pollution affects the Earth's climate by either absorbing or reflecting energy that can lead to climate warming or cooling, respectively [15]. Air pollutants, particularly nitrogen oxides (NO_x) and SO_2, can also lead to acid rain. Acid rain can harm vegetation by damaging tree leaves and stressing trees through changing the chemical and physical composition of the soil. Acid can reduce soil nutrient availability through leaching of nutrients such as magnesium or releasing toxic substances in soils such as aluminum [16].

Air pollution can reduce visibility. The visual range in the eastern US parks has decreased 90 miles to 15–25 miles due to man-made air pollution. In the West, the average visual range has decreased from 140 to 35–90 miles [17].

Air pollution can also directly damage plants and affect growth. Air pollution can affect a tree's functioning or health [18–22]. Some pollutants under high concentrations can damage leaves (e.g., sulfur dioxide, nitrogen dioxide, ozone), particularly of pollutant-sensitive species. Given the pollution concentration in most US cities, these pollutants would not be expected to cause visible leaf injury. Any potential harmful effects of carbon monoxide on trees are believed to be minimal. Some of the carbon monoxide can be converted to carbon dioxide and metabolized by the plants. Acid rain and air pollution can be a source of the essential plant nutrients of sulfur and nitrogen to enhance plant health and growth [16].

Particulate trace metals can be toxic to plant leaves. The accumulation of particles on leaves can reduce photosynthesis by reducing the amount of light reaching the leaf and thereby reduce plant growth and productivity. Particles can also affect tree disease populations with dust deposits leading to more fungal infections in some plant leaves [23].

Air pollution comes from numerous sources. Some pollutants, both gaseous and particulate, are directly emitted into the atmosphere and include sulfur dioxide, nitrogen oxides, carbon monoxide, and volatile organic compounds. Sulfur dioxide and nitrogen oxides are the primary causes of acid rain. Other pollutants are not directly emitted; rather, they are formed through chemical reactions. For example, ground-level ozone is often formed when emissions of NO_x and volatile organic compounds (VOCs) react in the presence of sunlight. Some particles are also formed from other directly emitted pollutants [1]. In the United States, emissions generally come from large stationary fuel combustion sources (e.g., electric utilities and industrial boilers and other processes (such as metal smelters, petroleum refineries, cement kilns, and dry cleaners), highway vehicles, and non-road mobile sources (such as recreational and construction equipment, marine vessels, aircraft, and locomotives).

8.2.1 Air Quality Regulations

In 1963, the Clean Air Act was passed in the United States. In 1970, a much stronger Clean Act was passed with Congress creating the US Environmental Protection Agency (EPA) and giving it the role in carrying out the Act. In 1990, the Act was revised and expanded giving the EPA broader authority to implement and enforce regulations to reduce air pollution emissions. Under the Clean Air Act, the EPA sets limits on the amount of pollution in the air and the emission of air pollutants. Individual states or tribes may have stronger air pollution laws, but they may not have weaker pollution limits. For several pollutants, the EPA establishes primary standards (permissible concentrations) that are designed to protect human health. A secondary standard is also established to prevent environmental and property damage. A geographic area with air quality that is cleaner than the primary standard is called an “attainment” area; areas that do not meet the primary standard are called “nonattainment” areas. In “nonattainment” areas, states and tribes develop state/tribal implementation plans to reduce air pollutants to allowable levels. These plans can include such items as cleaner vehicles, reformulated gasoline, changes in transportation policies (e.g., more buses or high-occupancy vehicle lanes), and vehicle inspection programs [24].

8.3 Tree Effects on Air Pollution

City trees have long been known to affect air quality. In the 1800s, parks in cities were referred to as “lungs of the city” due to the ability of the park vegetation to produce oxygen and remove industrial pollutants from the atmosphere [25]. This term was a form of an earlier expression “lungs of London,” which was first attributed to William Pitt, by Lord Windham in a speech in the House of Commons in 1808, during a debate on the encroachment of buildings upon Hyde Park [26].

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmospheric environment. The four main ways that urban trees affect air quality are the following [27]:

- *T*emperature reduction and other microclimatic effects
- *R*emoval of air pollutants
- *E*mission of volatile organic compounds and tree maintenance emissions
- *E*nergy effects on buildings

8.3.1 Temperature Reduction

Cities tend to have higher temperatures than rural areas due to “urban heat islands” [28, 29]. Tree transpiration and tree canopies affect air temperature, radiation absorption, heat storage, wind speed, relative humidity, turbulence, surface albedo, surface roughness, and mixing-layer height (i.e., height within which wind and surface substances (e.g., pollution) are dispersed by vertical mixing processes). These changes in local meteorology can alter pollution concentrations in urban areas [30]. Although trees usually contribute to cooler summer air temperatures, their presence can increase air temperatures in some instances [31]. For example, reduced windspeeds due to trees can increase air temperatures in treeless impervious areas on sunny days as cooler air is prevented from mixing with or dispersing the warm air coming off the impervious surfaces.

Maximum midday air temperature reductions due to trees are in the range of 0.04–0.2 °C per percent canopy cover increase [32]. Below individual and small groups of trees over grass, midday air temperatures at 1.5 m above ground are 0.7–1.3 °C cooler than in an open area [33] (tree effects on meteorology are discussed in more detail in Chap. 7). Reduced air temperature due to trees can improve air quality because the emission of many pollutants and/or ozone-forming chemicals is temperature dependent.

Topography also affects air temperatures (and pollution concentrations) through cold air drainage [34, 35]. The combination of natural landscapes (e.g., forests) and artificial landscapes (e.g., buildings) affects this cold air drainage. In Stuttgart, Germany, the identification of cold air drainage areas came to be labeled as the city's fresh air swathes. The maintenance of these natural ventilators became a critical component of the city's postwar planning policy [36].

In addition to temperature effects, trees affect wind speeds and hence mixing of pollutants in the atmosphere and local pollution concentrations [30, 37]. These changes in wind speeds can lead to both positive and negative effects related to air pollution. On the positive side, reduced wind speeds due to trees and forests will tend to reduce winter-time heating energy use in buildings by tending to reduce cold air infiltration into buildings, thereby reducing pollutant emissions associated with winter heating. For example, in residential neighborhoods in Central Pennsylvania, wind speed reductions by trees in the summer ranged from 28 to 46%, depending on tree cover in the neighborhood. However, even though the trees were mostly deciduous, winter wind speed reductions averaged 14–41% [37]. On the negative side, reductions in wind speed can reduce the dispersion of pollutants, which will tend to increase local pollutant concentrations. In addition, with lower windspeeds the height of atmosphere in which the pollutant mixes is often reduced. This reduction in the "mixing height" will also tend to increase pollutant concentrations as the same amount of pollution is now mixed within a smaller volume of air.

8.3.2 Removal of Air Pollutants

Healthy trees in cities can remove substantial amounts of air pollution. The amount of pollution removed is directly related to the amount or air pollution in the atmosphere. Areas with a high proportion of tree cover (e.g., forest stands) will remove more pollution and have the potential to have greater reduction in air pollution concentrations in and around these areas.

One acre of tree cover has an average pollution removal of about 100 pounds/year, but this value could range up to over 200 pounds/year in more polluted areas with long growing seasons (e.g., Los Angeles) (Fig. 8.1). These per acre pollution removal rates differ among cities according to the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables, such as temperature, wind speeds, and amount of solar radiation. Large healthy trees >30 in. in stem diameter remove approximately 60–70 times more air pollution annually (3.1 lbs/year) than small healthy trees <3 in. in diameter (0.05 lbs/year) (Fig. 8.2). As the number of trees in a size class tends to decrease with increasing size, while pollution removal tends to increase, overall pollution removal among tree 3-in. dbh classes can stay relatively stable (Fig. 8.3).

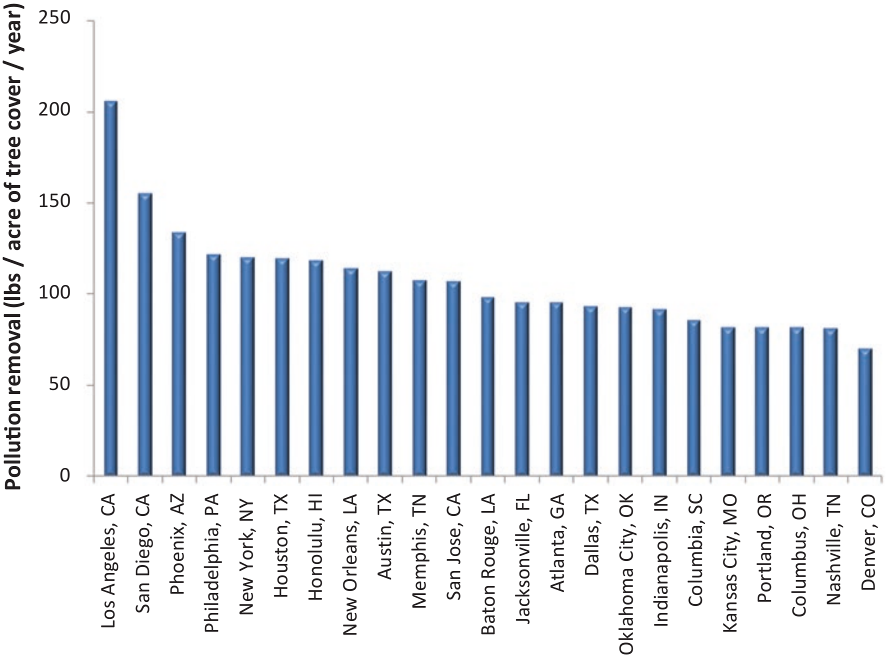

Fig. 8.1 Pollution removal values per acre of tree cover in select cities. Estimates assume a leaf area index of 6 and 10% evergreen species. Leaf area index is per unit tree cover and calculated as total leaf area (m^2) divided by tree cover (m^2)

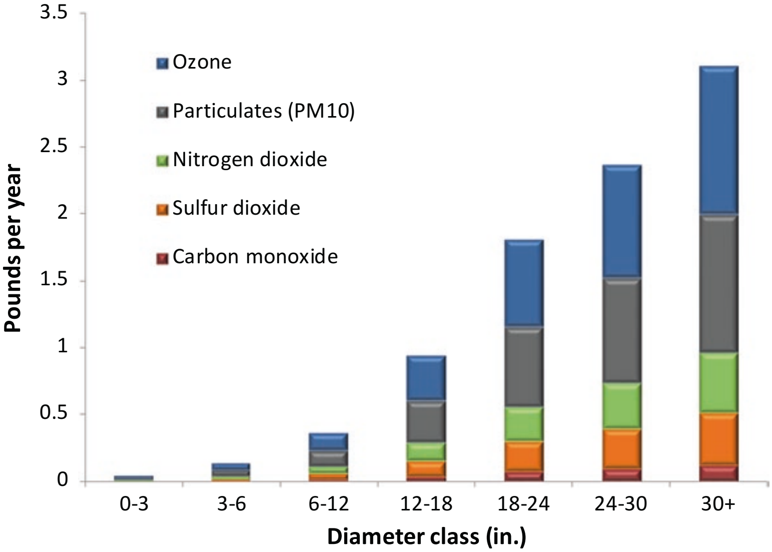

Fig. 8.2 Estimated pollution removal by individual trees by diameter class in Chicago, IL [38]

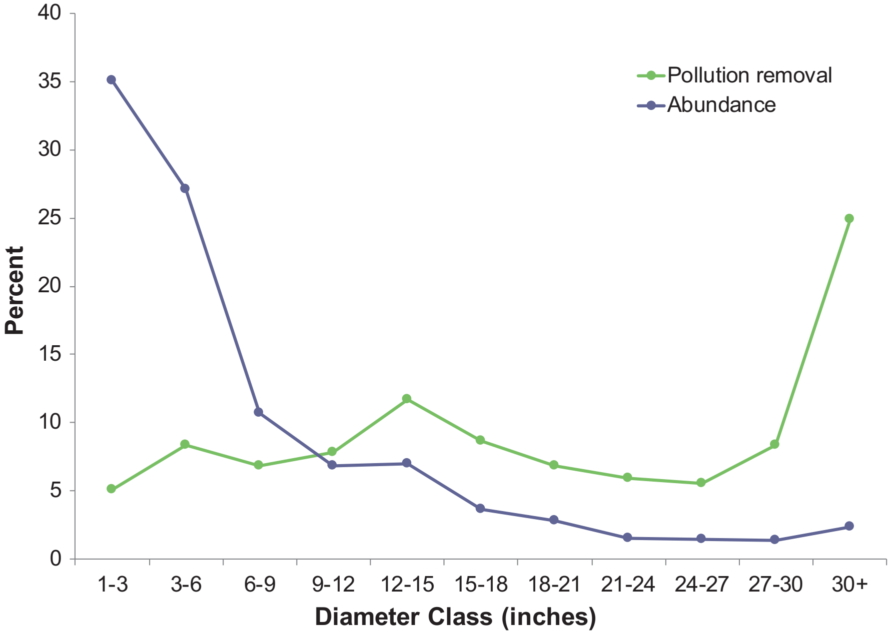

Fig. 8.3 Percentage of total population and pollution removal by diameter class, Philadelphia PA, 2012 [39]

Trees remove gaseous air pollution primarily by uptake through the leaf stomata, though some gases are removed by the plant surface. Once inside the leaf, gases diffuse into intercellular spaces and may be absorbed by water films to form acids or react with inner-leaf surfaces [23]. Trees also remove pollution by intercepting airborne particles on the plant surface. Although some particles can be absorbed into the tree [40–42], many intercepted particles are eventually resuspended back to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. Consequently, vegetation is only a temporary retention site for many atmospheric particles. The removal of gaseous pollutants is more permanent as the gases are often absorbed and removed within the leaf interior.

At the species level, pollution removal of gaseous pollutants will be affected by tree transpiration rates (gas exchange rates) and amount of leaf area. Particulate matter removal rates will vary depending upon leaf surface characteristics and area. Species with dense and fine-textured crowns and complex, small, and rough leaves would capture and retain more particles than open and coarse-textured crowns and simple, large, smooth leaves [23, 43]. Evergreen trees provide for year-round removal of particles. A species ranking of trees in relation to pollution removal is estimated in i-Tree Species (www.itreetools.org).

Although the individual tree and per acre tree cover values may be relatively small, the combined effects of large numbers of trees and tree cover in aggregate can lead to significant effects. Pollution removal by trees in cities can range up to

11,100 tons per year with societal values ranging up to $89 million per year in Jacksonville, FL, due to its large land area and tree cover [44]. Urban trees in the lower 48 United States are estimated to remove 822,000 tons of pollution per year with an estimated annual societal value of $5.4 billion per year [45].

Though the amount of air pollution removed by trees may be significant, the percent air quality improvement in an area will depend upon the amount of vegetation and meteorological conditions. Air quality improvement by trees in cities during daytime of the in-leaf season averages around 0.51% for particulate matter, 0.45% for ozone, 0.44% for sulfur dioxide, 0.33% for nitrogen dioxide, and 0.002% for carbon monoxide [44]. However, in areas with 100% tree cover (i.e., contiguous forest stands), air pollution improvements average around four times greater than city averages with short-term (1 h) improvements in air quality as high as 16% for ozone and sulfur dioxide, 9% for nitrogen dioxide, 8% for particulate matter, and 0.03% for carbon monoxide [44]. From a public health perspective, it is important to consider that even though percent air quality improvement from trees may not be very large, a small percent change in air quality can have a substantial impact on human health [2].

Percent improvement in air quality increases with increased percent tree cover and decreased mixing-layer heights. Although reduced mixing heights increase pollutant concentrations, it also increases the relative improvement from trees as volume of mixing in the atmosphere has decreased. To illustrate this reduction, consider identical air cleaners having the same rates of cleansing in cubic feet per hour, one cleaner is put in a large room, the other put in a small room, both with the same pollutant concentration. Though the cleaners are identical, the percent impact will be greater in the smaller room as there is less air to clean and less total pollution in the room.

8.3.3 Emission of Chemicals

While trees can reduce air pollution by changing the local microclimate and directly removing pollution, trees can also emit various chemicals that can contribute to air pollution [46]. Trees emit varying amounts of volatile organic compounds (e.g., isoprene, monoterpenes). These compounds are natural chemicals that make up essential oils, resins, and other plant products and may be useful in attracting pollinators or repelling predators. Complete oxidation of volatile organic compounds ultimately produces carbon dioxide, but carbon monoxide is an intermediate compound in this process. Oxidation of volatile organic compounds is an important component of the global carbon monoxide budget.

Emissions of volatile organic compounds by trees and other sources can also contribute to the formation of ozone, particularly during warm, sunny days in areas with high nitrogen oxide concentrations, which is common in the summer of many cities due to NO_x emissions from vehicles and power plants. However, in atmospheres with low nitrogen oxide concentrations (e.g., some rural environments), VOCs may actually remove ozone [47, 48]. Because VOC emissions are temperature dependent and trees generally lower air temperatures, increased tree cover can lower overall VOC emissions and, consequently, ozone levels in urban areas [49]. Volatile organic emissions of urban trees generally are <10% of total emissions in urban areas [50].

VOC emission rates vary by species. Nine tree genera that have the highest standardized isoprene emission rate [51, 52], and therefore the greatest relative effect on increasing ozone, are beefwood (*Casuarina* spp.), *Eucalyptus* spp., sweetgum (*Liquidambar* spp.), black gum (*Nyssa* spp.), sycamore (*Platanus* spp.), poplar (*Populus* spp.), oak (*Quercus* spp.), black locust (*Robinia* spp.), and willow (*Salix* spp.). However, due to the high degree of uncertainty in atmospheric modeling, results are inconclusive as to whether these genera will contribute to an overall net formation of ozone in cities (i.e., where ozone formation from VOC emissions is greater than ozone removal).

Trees generally are not considered as a source of atmospheric nitrogen oxides, though plants, particularly agricultural crops, are known to emit ammonia [53]. Emissions occur primarily under conditions of excess nitrogen (e.g., after fertilization) and during the reproductive growth phase. Highly fertilized turf can also lead to emissions of nitrogen.

Trees can make minor contributions to sulfur dioxide concentration by emitting sulfur compounds such as hydrogen sulfide and sulfur dioxide [54]. Hydrogen sulfide, the predominant sulfur compound emitted, is oxidized in the atmosphere to form sulfur dioxide. Higher rates of sulfur emissions from plants are observed in the presence of excess atmospheric or soil sulfur. However, sulfur compounds also can be emitted with a moderate sulfur supply.

Trees can contribute to particle concentrations in urban areas by releasing pollen [55] and emitting volatile organic and sulfur compounds that serve as precursors to particle formation [46]. In addition to the health effects of particles listed previously, pollen particles can lead to allergic reactions [56]. Examples of some of the most allergenic species are *Acer negundo* (male), *Ambrosia* spp., *Cupressus* spp., *Daucus* spp., *Holcus* spp., *Juniperus* spp. (male), *Lolium* spp., *Mangifera indica*, *Planera aquatica*, *Ricinus communis*, *Salix alba* (male), *Schinus* spp. (male), and *Zelkova* spp. [55].

Relatively large inputs of energy, primarily from fossil fuels, are often used to maintain vegetation structure. The emissions from these maintenance activities need to be considered in determining the ultimate net effect of urban forests on air quality. Various types of equipment are used to plant, maintain, and remove vegetation in cities. This equipment includes vehicles for transport or maintenance, chainsaws, backhoes, leaf blowers, chippers, and shredders. The combustion of fossil fuels to power this equipment leads to the emission of carbon dioxide and other chemicals such as VOCs, carbon monoxide, nitrogen and sulfur oxides, and particulate matter [57]. In California, gas-powered leaf blowers, hedge trimmers, and mowers are about to pass cars as the worst air polluters. By 2020, ozone-contributing pollutants from small off-road engines will exceed those same emissions from cars [58].

Trees in parking lots can also affect evaporative emissions from vehicles, particularly through tree shade. Increasing parking lot tree cover from 8 to 50% could reduce Sacramento County, CA, light-duty vehicle VOC evaporative emission rates by 2% and nitrogen oxide start emissions by <1% [59].

8.3.4 Energy Effects on Buildings

Trees reduce building energy use by lowering temperatures and shading buildings during the summer and blocking winds in winter [60]. However, they also can increase energy use by shading buildings in winter and may increase or decrease energy use by blocking summer breezes. Thus, proper tree placement near buildings is critical to achieve maximum building energy conservation benefits. Urban forests in the conterminous United States annually reduce residential building energy use to heat and cool buildings by $5.4 billion per year [45].

When building energy use is lowered, pollutant emissions from power plants are also lowered. Urban forests in the conterminous United States avoid the emission of thousands of tons of pollutants (carbon dioxide, nitrogen oxides, sulfur dioxide, methane, carbon monoxide, particulate matter <2.5 and 10 μm, and volatile organic compounds (VOCs)) valued at $2.7 billion per year [45]. Some utilities (e.g., Sacramento Municipal Utility District) have funded millions of dollars for tree planting to reduce energy use [61].

8.3.5 Trees Along Roadways

Trees along roadways can also affect how automobile emissions are dispersed to nearby residents [62]. Though a relatively new area of research, trees and bushes along roadways offer a complex and porous structure that can increase air turbulence and promote mixing as air flows through and around the vegetation. These vegetation effects can potentially reduce pollutant concentrations near roadways. However, tree canopies can also reduce wind speed and mixing-layer heights [30], which can reduce dispersion and potentially increase concentrations in the highway or street corridor. Modeling, wind tunnel experiments, and field measurements have evaluated the role of vegetation on pollutant concentrations near roadways [63–67]. Variables such as the vegetation type, height, and thickness influence the extent of mixing and pollutant deposition, although specific interrelationships of these factors have not been identified. In addition, the porosity of vegetation relative to solid structures may promote wind flow off the road and reduce on-road pollutant concentrations, although the resulting effect on downwind concentrations may be variable [68].

8.3.6 Overall Effect of Vegetation on Air Pollution

There are many factors that determine the ultimate effect of trees on pollution. Many tree effects are positive in terms of reducing pollution concentrations. For example, trees can reduce temperatures and thereby reduce emissions from various sources, and they can directly remove pollution from the air. However, the altering of wind patterns and speeds can affect pollution concentration in both positive and negative ways. Also plant compound emissions and emissions from vegetation maintenance can contribute to air pollution. Various studies on ozone, a chemical that is not directly emitted but rather formed through chemical reactions, help illustrate the cumulative and interactive effects of trees.

One model simulation illustrated that a 20% loss in forest cover in the Atlanta area due to urbanization led to a 14% increase in ozone concentrations [49]. Although there were fewer trees to emit volatile organic compounds, an increase in Atlanta's air temperatures due to the increased urban heat island, which occurred concomitantly with tree loss, increased volatile organic compound emissions from the remaining trees and other sources (e.g., evaporative emissions from cars), and altered ozone chemistry such that concentrations of ozone increased. This is an example of how decision makers might achieve counterintuitive results based on partial information, i.e. not systems thinking, as discussed in Chap. 1 and illustrates the importance of modeling to test well-intended policies before undertaking implementation.

Another model simulation of California's South Coast Air Basin suggests that the air quality impacts of increased urban tree cover may be locally positive or negative with respect to ozone. However, the net basin-wide effect of increased urban vegetation is a decrease in ozone concentrations if the additional trees are low VOC emitters [69].

Modeling the effects of increased urban tree cover on ozone concentrations from Washington, DC, to central Massachusetts revealed that urban trees generally reduce ozone concentrations in cities but tend to slightly increase average ozone concentrations regionally. Trees changed pollution removal rates and meteorology, particularly air temperatures, wind fields, and mixing-layer heights, which, in turn, affected ozone concentrations. Changes in urban tree species composition had no detectable effect on ozone concentrations [30]. Modeling of the New York City metropolitan area also revealed that increasing tree cover 10% reduced maximum ozone levels by about 4 ppb, which was about 37% of the amount needed for attainment of the ozone air quality standard, revealing that increased tree cover can have a significant impact on reducing peak ozone in this region [70].

Though reduction in wind speeds can increase local pollution concentrations due to reduced dispersion of pollutants and mixing height of the atmosphere, altering of wind patterns can also have a potential positive effect. Tree canopies can potentially prevent pollution in the upper atmosphere from reaching ground-level air space.

Measured differences in ozone concentration between above- and below-forest canopies in California's San Bernardino Mountains have exceeded 50 ppb (a 40% reduction in ozone concentrations) [71]. Forest canopies can limit the mixing of upper air with ground-level air, leading to significant below-canopy air quality improvements. However, where there are numerous pollutant sources below the canopy (e.g., automobiles), the forest canopy could increase concentrations by minimizing the dispersion of the pollutants away at ground level. This effect could be particularly important in heavily treed areas where automobiles drive under tree canopies (Fig. 8.4). At the local scale, pollution concentrations can be increased if trees (a) trap the pollutants beneath tree canopies near emission sources (e.g., along roadways) [68, 72–74], (b) limit dispersion by reducing wind speeds, and/or (c) lower mixing heights by reducing wind speeds [30, 75]. However, standing in the interior of stands of trees can offer cleaner air if there are no local ground sources of emissions (e.g., from automobiles) nearby. Various studies [76, 77] have illustrated reduced pollutant concentrations in the interior of forest stands compared to outside of the forest stand.

While increased tree cover will enhance pollution removal and reduce summer air temperatures, local scale forest designs need to consider the location of pollutant sources relative to the distribution of human populations to minimize pollution

Fig. 8.4 Design of vegetation near roadways is important to minimize potential negative effects, such as trapping of pollutants (image source: D. Nowak)

concentrations and maximize air temperature reduction in heavily populated areas. Forest designs also need to consider numerous other tree impacts that can affect human health and well-being (e.g., impacts on ultraviolet radiation, water quality, aesthetics, etc.).

8.3.7 Health Effects

There are numerous studies that link air pollution to human health effects. With regards to trees, most studies have investigated the magnitude of the effect of trees on pollution removal or concentrations, while only a limited number of studies have looked at the estimated health effects of pollution removal by trees. In the United Kingdom, woodlands are estimated to prevent between five and seven deaths and between four and five hospital admissions per year due to reduced pollution of sulfur dioxide and particulate matter (PM10) [78]. Modeling for London estimates that 25% city tree cover removes 90.4 metric tons of PM10 pollution per year, which equates to a reduction of two deaths and two hospital stays per year [79]. Nowak et al. [80] reported that the total amount of $PM_{2.5}$ removed annually by trees in ten US cities in 2010 varied from 4.7 tons in Syracuse to 64.5 tons in Atlanta, with health values ranging from \$1.1 million in Syracuse to \$60.1 million in New York City. Health impacts from air pollution removal by US urban trees in 2010 included the avoidance of 670 deaths and 575,000 acute respiratory incidences [75].

8.3.8 Importance of Trees to Clean Air

In September 2004, the US Environmental Protection Agency (EPA) released a guidance document titled “Incorporating Emerging and Voluntary Measures in a State Implementation Plan (SIP)” [81]. This EPA guidance details how new measures, which may include “strategic tree planting,” can be incorporated in SIPs as a means to help meet air quality standards set by the EPA. As many of the standard strategies to meet clean air standards may not be sufficient to reach attainment, new and emerging strategies (e.g., tree planting, increasing surface reflectivity) may provide a means to help an area reach compliance with the new clean air standard for ozone. “In light of the increasing incremental cost associated with stationary source emission reductions and the difficulty of identifying additional stationary sources of emission reduction, EPA believes that it needs to encourage innovative approaches to generating emissions reductions” [81]. As many urban areas are designated as nonattainment areas for the ozone clean air standard and are required to reach attainment, trees in cities may play an important role in reaching clean air standards and can be integrated within SIPs [82].

8.4 Climate Change

Climate change refers to any significant change in measures of climate (e.g., temperature, precipitation) that occurs over an extended period (e.g., decades). This change could be due to natural factors and/or from human activities. Increasing levels of atmospheric carbon dioxide and other "greenhouse" gases (e.g., methane, chlorofluorocarbons, nitrous oxide) are contributing to an increase in atmospheric temperatures by the trapping of certain wavelengths of heat in the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) report [83] states that "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased." "Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years." Observed long-term changes in climate include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, strengthening wind patterns, and aspects of extreme weather events including droughts, heavy precipitation, and heat waves. Some future effects of climate change are projected to be (a) warmer and fewer cold days and nights over most land areas; (b) warmer and more frequent hot days and nights over most land areas; (c) increased frequency and duration of heat waves; (d) increased frequency, intensity, and number of heavy precipitation events; and (e) increased incidence and/or magnitude of extreme high sea levels. The societal and ecological impacts of climate change include potential changes to heat-related deaths, length of growing seasons, plant hardiness zones, leaf-out and flowering dates, and bird wintering ranges [15]. The projected average surface temperature warming by 2100 (relative to the 1980–1999 temperature average) is likely between 1.8 and 4.0 °C based on climate modeling projections. Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be between 0.3 °C and 4.8 °C depending upon model simulation used [83].

As carbon dioxide is one of the dominant greenhouse gases and trees can influence carbon dioxide concentrations, tree effects on carbon dioxide are addressed in this section. Fossil fuel combustion is the primary source contributing to carbon dioxide emissions. Major sources of fossil fuel combustion include electricity generation, transportation, industrial processes, residential, and commercial land use. Electricity generation contributes approximately 39% of carbon dioxide emissions from fossil fuel combustion in the United States, while transportation contributes approximately 33% [84].

8.5 Tree Effects on Climate Change

Tree effects on climate change are similar to the types of effects of trees on air pollution. They (a) remove carbon dioxide from the atmosphere, (b) emit carbon dioxide, and (c) reduce air temperatures and alter building energy use and consequently emissions from power plants and other sources (e.g., evaporation of gasoline).

8.5.1 Carbon Storage and Annual Sequestration

Trees, through their growth process, directly remove carbon dioxide from the atmosphere and sequester the carbon within their biomass. Carbon storage by trees in a city can range up to over 1.3 million tons of carbon with societal value of approximately $28 million (New York, NY) [85]. Annual removal of carbon by trees in a city can reach over 45,000 tons of carbon per year with a value of approximately $1.0 million per year (Atlanta, GA). One acre of tree cover will likely store, on average, around 34 tons of carbon and remove about 1.2 tons of carbon per year (Figs. 8.5 and 8.6).

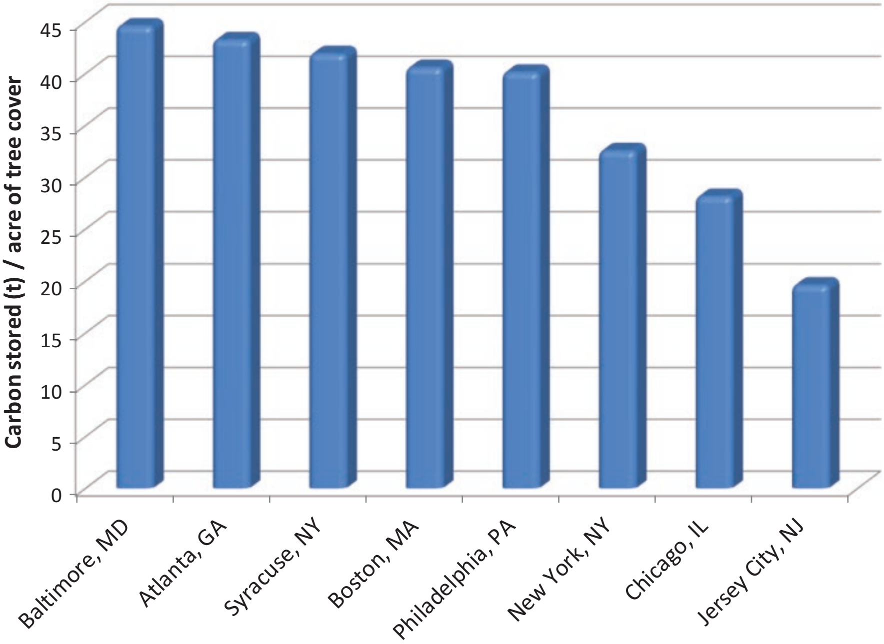

Fig. 8.5 Carbon storage per acre of tree cover in select cities [85, 86]

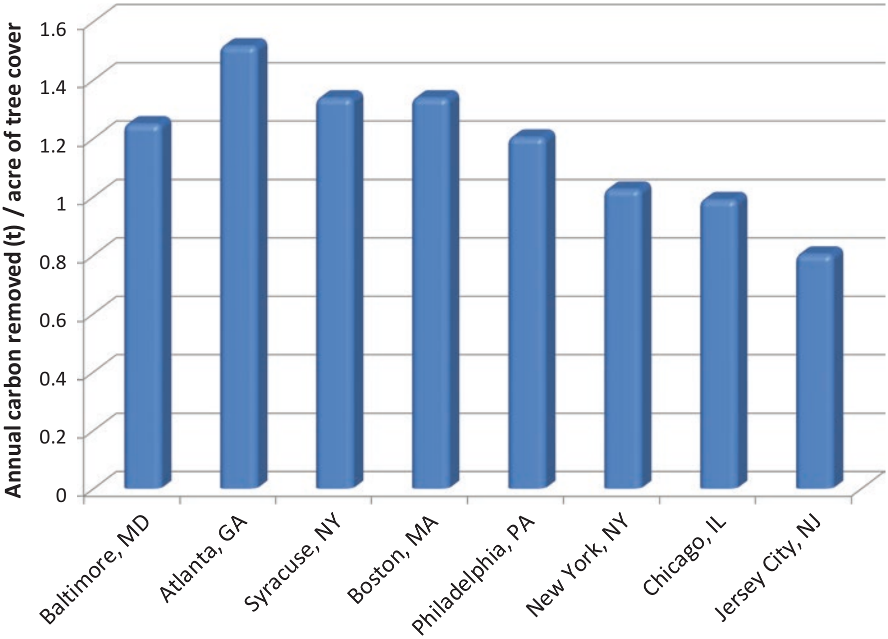

Fig. 8.6 Annual carbon removed per acre of tree cover in select cities [85, 86]

Large trees >30 in. in trunk diameter store approximately 800–900 times more carbon than small trees <3 in. in diameter (Fig. 8.7). Large healthy trees also remove about 50 times more carbon annually than small healthy trees (Fig. 8.8). Even though there are more small trees in cities, large trees tend to store more carbon overall (Fig. 8.9).

The combined effects of individual trees across a landscape can be significant in terms of carbon storage and annual removal. Carbon storage by urban forests in the conterminous United States is estimated at 919 million tons with an estimated value of $119 billion. Annual gross carbon sequestration by urban forests is estimated at 36.7 million tons with an estimated value of $4.8 billion [45]. The annual removal rate by urban trees is about 2.2% of the estimated total carbon emissions in the United States in 2014 (6123 million tons of carbon dioxide/year) [84].

In addition to trees, soils in urban areas can also sequester significant amounts of carbon as carbon from plants and animals is transferred to soils. In forest ecosystems in the United States, 38% of the total carbon is stored in the soil environment (18.9 billion tons of soil carbon) [88]. The amount of carbon in urban soils in the United States is estimated at around 2.1 billion tons [89].

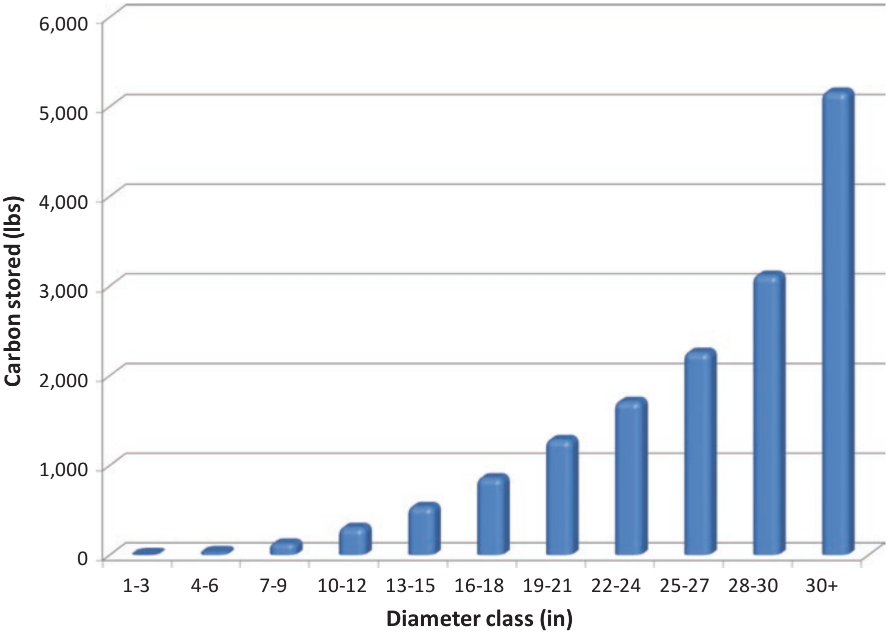

Fig. 8.7 Average carbon stored per tree by diameter class in Chicago [87]

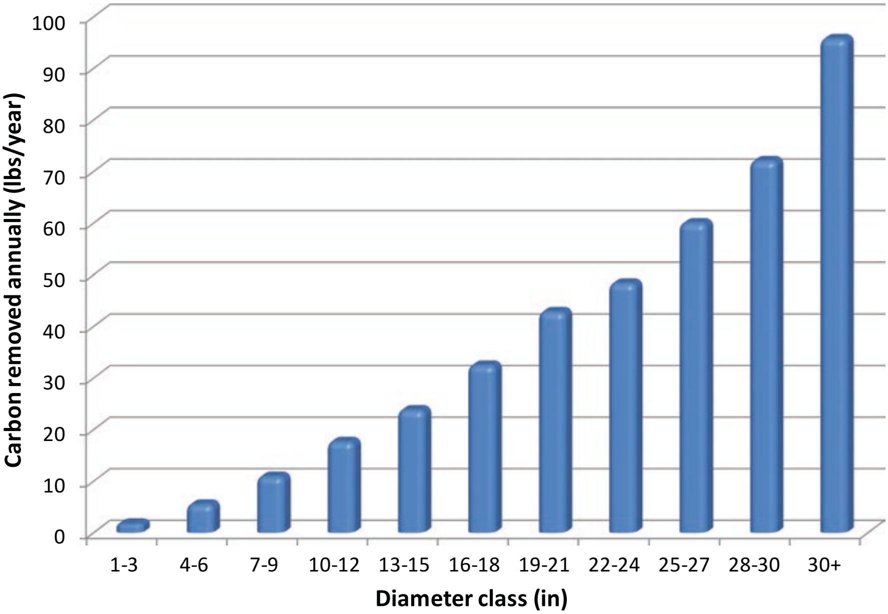

Fig. 8.8 Average carbon removal per tree per year by diameter class in Chicago [87]

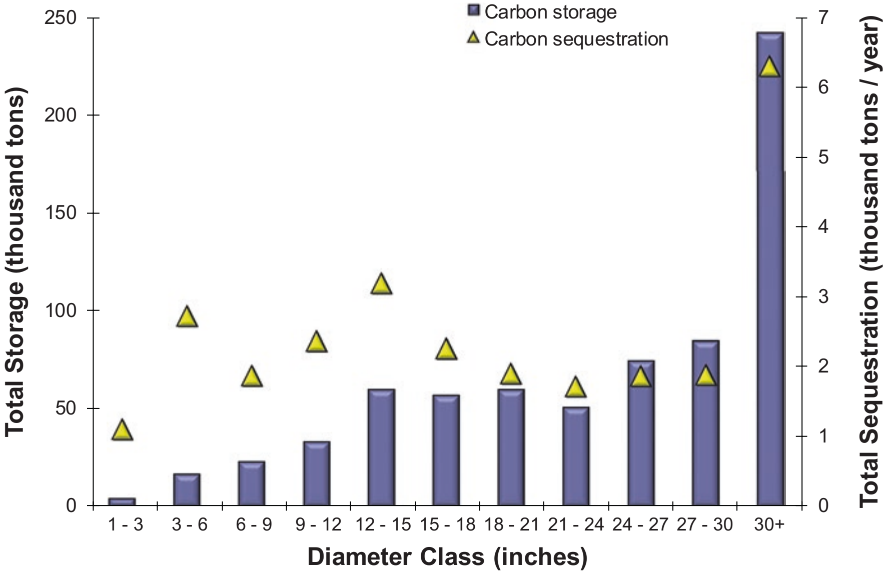

Fig. 8.9 Estimated total carbon storage and sequestration by diameter class, Philadelphia PA, 2012 [39]

8.5.2 *Carbon Emissions: Carbon Cycling*

Although trees can sequester and store significant amounts of carbon in urban areas, this carbon eventually cycles back to the atmosphere through natural or human-accelerated processes. When a tree dies and the wood is allowed to decompose or is burned, most of the stored carbon goes back to the atmosphere, though some of the carbon can be retained in soils. Thus, the net carbon storage in a given area will cycle through time as the population grows and declines. When forest growth (carbon accumulation) is greater than decomposition, net carbon storage increases.

When forests are removed and/or soils disturbed, net carbon storage will diminish through time as accumulated carbon in both trees and soil will convert back to carbon dioxide through decomposition. Various management practices can be used to help enhance the long-term impacts of urban forests on atmospheric carbon [90]. Keeping soils intact and utilization of tree biomass into long-term products such as furniture can delay carbon releases for long periods. Composting plant material can help facilitate carbon retention in soils. Using trees to reduce energy use and carbon emissions can avoid carbon emissions into the atmosphere.

Tree maintenance activities can also offset tree carbon sequestration gains through carbon emissions from maintenance equipment (e.g., from vehicles, chainsaws, backhoes, etc.). Because tree management can use relatively large amounts of fossil fuel-based energy to maintain vegetation, the emissions from maintenance/management activities need to be considered in determining the ultimate net effect of urban forests on global climate change. (See Chap. 11 for discussion of lower energy-requiring urban *ecological* landscaping.)

If trees are maintained using fossil fuels and do not offset emissions from other sources (e.g., reducing building energy use), maintained trees will ultimately be net emitters of carbon at some point in the future. This point will occur when carbon emissions due to maintenance activities exceed the total storage capacity of the tree or stand [90]. The number of years until carbon emissions exceed the carbon capacity of the site varies by tree species, tree density, and maintenance intensity. For maintained trees that do not survive the first few years after planting, carbon deficits can occur from the onset because carbon removal by the trees is less than the initial carbon inputs invested into planting the trees. If removed trees are used for energy production, they can also help reduce carbon emissions from fossil fuel burning power plants.

8.5.3 Reduced Carbon Emissions Through Cooler Temperatures and Reduced Energy Use

As discussed previously, trees can help mitigate heat island effects and reduce energy use and consequently carbon emissions from power plants [91, 92]. Vegetation designs to reduce air temperatures and building energy use in cities can lead to reduced carbon emissions from power plants and other sources and consequently help avoid emissions of carbon dioxide. The cooling effect of trees may be particularly important in the future due to projected warmer temperatures due to climate change [93]. Cities may be particularly warmer in the future due to climate change concomitant with urban heat islands that are already warming urban areas.

8.5.4 Climate Change Effects on Trees

Not only can trees affect the causes and effects of climate change, but climate changes will also affect the urban tree composition. Future changes in temperature and precipitation, along with increasing levels of carbon dioxide, are likely to lead to shifts in natural and cultivated species in cities. As urban areas already exhibit climatic differences compared to rural environs, due in part to numerous artificial surfaces and high level of fossil fuel combustion, climate change impacts may be exacerbated in these areas. These environmental changes can affect urban vegetation structure and functions in multiple ways.

Tree stress and/or decline may be increased due to elevated air temperatures, possible increased air pollution concentrations due to temperature changes, limited or excessive moisture, and intensified storm damage. Conversely, some trees/plants may benefit from increased air temperatures [94], increased air pollutants (e.g., sulfur and nitrogen) that can have a fertilizing effect [22], and/or increased CO_2 levels that may enhance growth rates [95]. If the environmental stresses induced by global climate change reduce tree growth and transpiration, or increase tree mortality, then tree benefits could decrease. However, if stresses are minimal, then carbon sequestration and pollution removal by trees may be enhanced with increased concentrations of carbon dioxide and air pollutants.

Increased plant stress/decline and/or storm damage frequency/intensity has the potential to increase tree maintenance activities needed to sustain healthy tree cover, thereby increasing associated maintenance emissions. In addition, if tree stress/mortality increases, it is likely that management will respond with shifts toward species that are better adapted to the changing climate. Along with changes in urban vegetation structure due to humans, species changes will likely also occur in more natural areas as species compositions shift with altered environments [96, 97]. Thus, the composition of urban forests may change in the future due to both natural and human-facilitated species changes due to a changing climate.

8.6 Conclusion

Overall, trees and forests have a positive effect on human health and well-being by improving air quality and reducing greenhouse gases, mainly through reducing air temperatures and energy use and through direct pollution removal and carbon sequestration. However, trees also have some negative effects related to the emission of VOCs, pollen, and carbon (via decomposition) and the lowering of wind speeds. Local scale forest designs near pollutant sources need to consider that trees alter wind flows and can limit pollution dispersion and increase local pollutant concentrations (e.g., along streets), but trees can also protect sites from pollutant emissions and lower pollution concentrations (e.g., in forest stands). By understanding the effects of trees and forests on the atmospheric environment, managers can design appropriate and healthy vegetation structure in cities to improve air quality and consequently human health and well-being for current and future generations.

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Chapter 9
Nutrient Biogeochemistry of Urban Systems

Dennis P. Swaney

Abstract This chapter highlights some of the features of nutrient flows through urban areas. Cities represent foci of human activity and are thus centers of resource consumption. Anthropogenic contributions of nutrients (mainly nitrogen (N) and phosphorus (P)), and especially their consumption as food in urban areas, are associated with nutrient loads in human waste, which is channeled to waste treatment facilities, to landfills, and, ultimately, to the regional environment. Other significant contributions include atmospheric N deposition associated with industrial and vehicular combustion processes and N and P fertilizer applied to urban lawns and gardens. The concentration of these nutrients in urban regions, combined with their rapid movement in water flows facilitated by the impervious surfaces and drainage networks of cities, results in high nutrient loads to local and regional waters. Intensification of storm events in future climate scenarios should exacerbate potential nutrient flows from cities. High N and P loads, especially when out of balance with other nutrients such as silicon (Si), represent problems for water quality management.

Keywords Urban ecosystem · Stormwater · Nitrogen · Phosphorus · Silicon · Ecosystem metabolism · Foodshed

9.1 Nutrients and Ecosystem Metabolism of Cities, Foodsheds, and Receiving Waters

In this chapter, we highlight some of the features of nutrient flows through urban areas. Cities represent foci of human activity and thus human consumption of resources, including energy, food, and water. Anthropogenic contributions of nutrients (mainly nitrogen (N) and phosphorus (P)), and especially their consumption in

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urban areas, represent a highly important, even critical, contribution to the global cycling of these elements (Box 9.1). The demand for food drives these "urban engines" of human waste production and its associated nutrient load, which is channeled to waste treatment facilities, to landfills, and, ultimately, to the regional environment. The emissions associated with energy production and vehicular transportation in and around cities represent sources of nitrogen fixed from the atmosphere as part of the fuel combustion process. The other main source of industrially fixed N, nitrogenous fertilizer, is not a dominant component of the N budget in urban centers but can be locally important in suburban areas and other urban spaces such as parks.

The water demand of cities (considered in Chap. 9) provides the carrier for much of this waste stream in sewage flows, and the impervious surfaces characteristic of engineered urban environments promote the rapid surface flow of runoff following rainfall and snowmelt events, thereby transporting nutrients more quickly and efficiently from urban areas to receiving waters than regions with higher proportions of porous landscape.

Box 9.1: Net Anthropogenic Nutrient Inputs (NANI and NAPI)

A widely used convention for nutrient accounting at watershed and regional scales considers the net inputs of human-generated (anthropogenic) nutrients. For N, this is referred to as the net anthropogenic nitrogen input (NANI) methodology and for P, NAPI [1–3]. While some individual studies vary, NANI considers synthetic N fertilizer inputs, crop N fixation, atmospheric deposition of oxidized N (NO_y), and the net demand of N for food and livestock feed in a region (assumed to equal the transport of N into or out of the region) (Fig. B1). The NAPI approach includes the corresponding flows but generally assumes that atmospheric sources of P (e.g., long-distance transport of dust) are negligible and that there is no analog in P for N fixation, so that the calculations are simpler. Nutrient accounting has typically been conducted on a watershed basis, so that inputs of riverine nutrients can be assumed to be nonexistent (watersheds are defined to have only riverine outflows), though Han et al. have recently considered the case of net anthropogenic nutrient accumulation (NANA, NAPA) in urban systems [5, 6], which includes the difference between inflows and outflows of riverine nutrients.

Numerous studies have noted that the NANI to a region is well-correlated with its riverine N export and the slope of the generally linear relationship between NANI and N export can be interpreted as the proportion of anthropogenic N sources flowing to coastal waters; the remaining fraction, the "N retention" of the region, typically ranging from 70% to 85% of the total, is largely attributable to denitrification processes in the landscape that transform the reactive N back to the atmosphere (though storage in organic matter and groundwater pools also can account for some retention). Most of these studies

(continued)

Box 9.1 (continued)

have been conducted in large, mixed land use watersheds (1000s of km^2) [7, 8], though some urban areas and their foodsheds, including Paris, Beijing, and New York, have been investigated in recent years [4–6, 9–11].

Urban areas represent an extreme in that the net food/feed term is almost entirely due to human food demand and thus represents an import of nutrients to urban regions, in contrast to agricultural regions which can represent an import (for livestock feed) or an export (in grain or other crops to meet demands beyond the production region). Urban areas also represent regions of relatively high impervious surface, and thus high hydrological response to storms and short hydrological residence times, suggesting little time for biogeochemical processing of nutrients, and a high proportion of nutrient delivery in runoff waters.

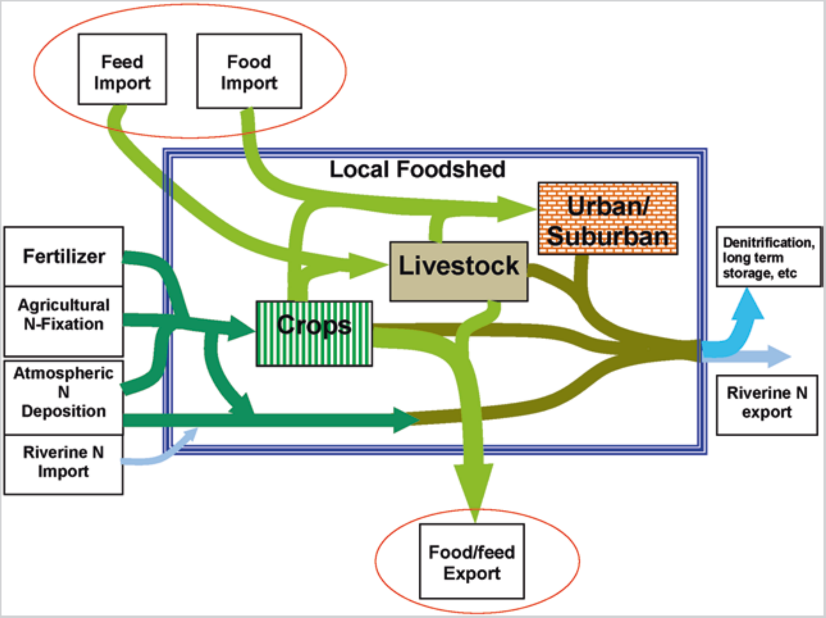

Fig. B1 Schematic diagram of net anthropogenic nutrient inputs to the local foodshed of a city in relation to riverine nutrient import and exports. Net riverine exports (export-import to the region) can be related to the other terms assuming a mass balance of inflows and outflows [1–5]. Food/feed imports and exports can also be combined into a single "net" term which may represent a net import or export. While nitrogen accounting includes all of the terms above, the analogous diagram for phosphorus would have no atmospheric or fixation terms.

Considered from an ecological standpoint, the “metabolism” of a city is “heterotrophic” overall, consuming more organic material (food) than it produces [4, 12]. The nutrients which subsidize cities originate in the “autotrophic” regions comprising the “foodshed” or “foodprint” of the city, defined as the area necessary to grow food to support its population [9, 13]. Historically, such regions were found within and adjacent to city boundaries, but the modern transportation network has homogenized the global diet and scattered city foodsheds to distant regions of the globe. Fertilizer nitrogen applied to corn or soybeans in Iowa may be consumed as pork in Shanghai.

Some cities, such as Paris, still rely on relatively nearby sources to provide nutrients for their inhabitants. Billen and others estimate that approximately 50% of the Parisian food supply originates from within the (autotrophic) Seine basin (Fig. 9.1a) [9]. In contrast, many other cities, including New York, rely on long-distance transport for most of their nutrient resources. The consequences of the globalization of nutrient flows and their concentration in urban centers of consumption remain to be fully explored—but as we have seen, these processes have come to dominate nutrient flows in many parts of the globe and thus must have profound impacts.

In contrast to the towns and villages of a century or two ago, the nutrients originating in a city’s foodshed and drawn to the “urban maw” now ultimately can fuel both autotrophic and heterotrophic processes in their receiving waters irrespective of the physical location of the foodshed. Excess nutrients from urban effluents can overfertilize ecosystems downstream, resulting in cycles of overproduction, die-off, and oxygen-consuming breakdown of the organic matter. The magnification of nutrient load is a serious problem for environmental management and planning in urban areas, with major environmental and human health consequences due to nutrient enrichment and imbalances, including eutrophication, harmful algal blooms, development of hypoxic areas (low-oxygen areas, also called “dead zones”), and declines in recreational areas and fisheries. In surveying coastal waters of the United States, Bricker et al. found that 65% of the estuaries assessed (78% of the area) showed symptoms of moderate to high eutrophication, many as a direct result of nutrient loads from coastal cities [14]. The complete story of the biogeochemistry of urban ecosystems, including their foodsheds and receiving waters, is still unfolding, but it seems clear that these economic engines have transformed patterns of biogeochemical processes from local to global scales.

9.2 The Unique Character of Cities

Every city has its own personality, but they all have many features in common. The urban center of a modern city can be seen as an endpoint on a continuum of nutrient loading, chemical transformations, and ecological responses between “developed” and “undeveloped” areas [15]. Suburban areas are intermediate in the extent of food consumption, green space, road density, housing density, and many other factors that affect biogeochemical processes. As we will see below, these factors have consequences for nutrient cycling and environmental quality.

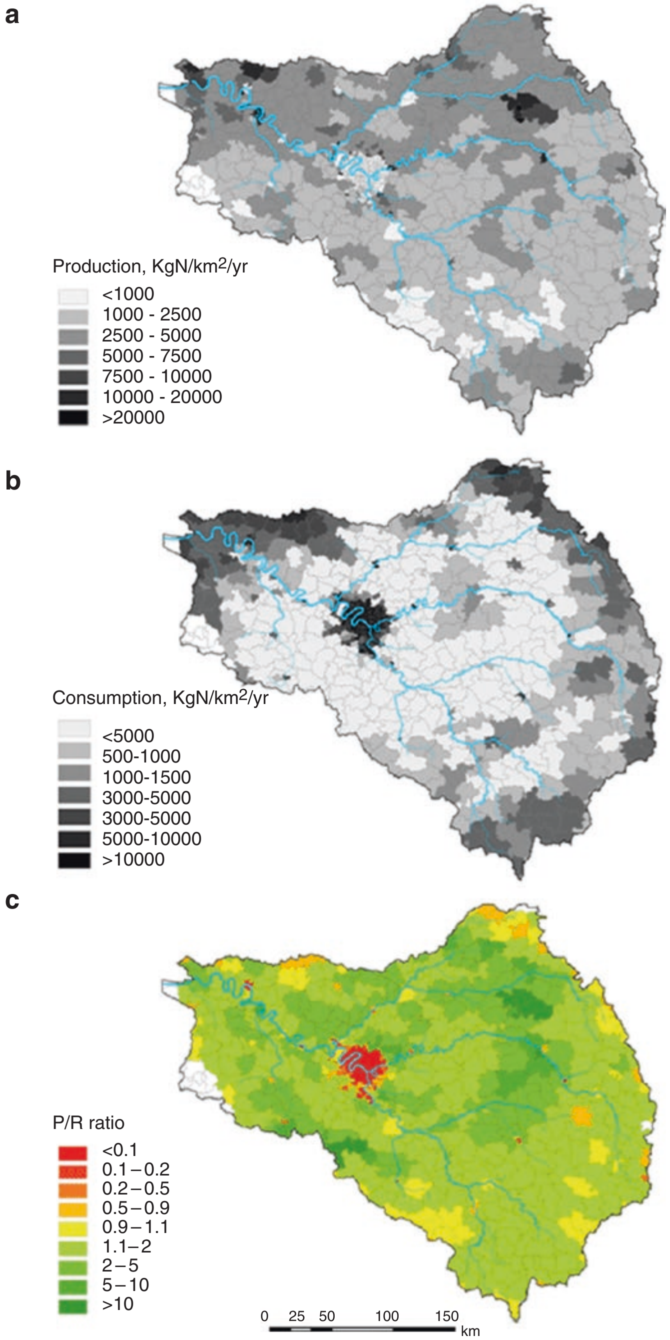

Fig. 9.1 (**a**) Spatial distribution of net primary production by agricultural and forested land (Autotrophy), (**b**) total heterotrophic consumption by human and domestic animals and by forest communities (Heterotrophy), and (**c**) the ratio of autotrophy:heterotrophy within the region of Paris and the Seine basin [4]. In panel (**c**), red values indicate dominance of heterotrophy (consumption of organic matter, i.e., food and feed) with a ratio < 1; green values indicate dominance of autotrophy (production of organic matter and consumption of nutrients) with a ratio > 1, which includes the local foodshed. The metropolitan area of Paris appears as the red region at the center of the Seine basin (used with permission)

The differences between urban centers and the countryside that are reflected in the non-visual sensory experiences are also manifest in the biogeochemical processes of cities. The smell of a city reflects the food requirements of its inhabitants and combustion of fuel to transport them from place to place, both of which provide inputs of nutrients to the city. The paved roads, sidewalks, parking lots and the concrete or brick-and-mortar buildings with shingled or metal roofs, and the concrete lined drainages and waterways that comprise the "infrastructure" shell of the city affect the hydrological response of cities to rain and snowfall, preventing seepage into the ground and accelerating movement of water through the city, with consequences for transport of nutrients through and out of the city. These features, together with the effect of the "urban canyon," also can raise the temperature and shape the micrometeorology of cities and possibly the rates of weathering of structures and pavement. The meteorological environment of the city determines the duration of the growing season and timing of critical events of urban vegetation, such as the emergence of buds in the spring and dropping of leaves in the fall, relating to the cycling of nutrients from urban soils to vegetation and back again.

The location of a city, typically along a river, estuary, or other major water body, is usually the result of its origins as a center of trade, which originally required the proximity to water transport. One consequence of this is the inevitable impact of cities on the quality of these waters through runoff from their relatively impervious surfaces and direct discharge of sewage wastes from their inhabitants.

9.3 Nutrient Biogeochemistry

Modern global nutrient cycles are very heavily influenced, or effectively generated, by human activities. Nutrients so generated are termed "anthropogenic" (Box 9.1). Nitrogen (N) and phosphorus (P) are usually the main subjects of discussions of nutrient cycling and biogeochemistry because of their important roles in fueling all of the organisms which comprise ecosystems and the enormous impact of human activities on their global cycling through the environment. A third element, silicon (Si), comes into play when discussing the biology of aquatic food chains and nuisance algal species, because of its role as an essential nutrient in the growth of diatoms, a generally benign class of algae which is at the base of many aquatic food chains. We briefly review some features of these nutrients and the roles urban areas play in their biogeochemical cycles [16].

9.3.1 Nitrogen

While most of Earth's nitrogen exists in the atmosphere in the inert form of N_2 gas, probably the most familiar form of nitrogen is the N in enzymes and other proteins, which are essential components of all living things. In the absence of human activity, atmospheric N_2 can be transformed into organic forms by the action of some "nitrogen-fixing" plants and bacteria. When these organisms die, the organic N is broken down ("mineralized") into inorganic forms by other organisms ("decomposers"), and these "reactive" forms of N (mainly nitrate (NO_3^-), nitrite (NO_2^-), and ammonia (NH_3) or its ionic form, ammonium (NH_4^+)) are readily taken up by plants as essential nutrients. These processes provide the basis of N nutrition in Earth's food chains. Today, naturally occurring nitrogen fixation is largely overshadowed by N fixation by legume crops and by industrially produced nitrogen fertilizer to supply agriculture.

Another important class of bacteria, "denitrifiers," transforms nitrate into gaseous forms of nitrogen (N_2O, a potent greenhouse gas, and N_2, the major constituent of the atmosphere), which then can dissipate by diffusion into the atmosphere. These microbes use NO_3 instead of O_2 for respiration in typically wet "anoxic" environments such as those found in wetlands, riparian areas, or in benthic zones where O_2 is not available, releasing nitrogen in the process, thereby removing it as a potential source of eutrophication in water bodies downstream, and providing essentially the same "service" as a tertiary treatment process in a municipal waste treatment facility.

Most nitrogen entering urban regions does so in the form of food protein. The US population consumes around 5–6 kg N per person per year. In urban regions, most of this nitrogen finds its way to the sewer system and, in most cases, to a municipal waste treatment facility where it is processed. Some lower-density urban and suburban areas rely on septic systems for treatment. Depending upon the nature and degree of treatment, this nitrogen may return to the atmosphere after denitrification, to the soil as sewage sludge "amendments," or to receiving waters in treated effluent. In addition, nitrogen in food waste may find its way through the solid waste stream to landfills or, in some less affluent urban regions, to local garbage dumps.

Other sources of N to urban and suburban areas include fertilizer and atmospheric deposition of N. In particular, compared to the beginning of the twentieth century, global nitrogen flows to the landscape are over tenfold larger, mainly due to the impact of the development of the Haber-Bosch process for "fixing" nitrogen from the atmosphere (Box 9.1). This industrial process permits N_2 to be transformed into biologically reactive forms that can be used as plant fertilizers on cropland and in other processes. As of the year 2000, about 47% of the global population lived in urban areas, many in very large cities, so it is fair to say that the Haber-Bosch process has made possible the development of the modern metropolis via the increased productivity of modern agriculture. It is also true that fertilizer application rates on suburban lawns can exceed those in croplands (Table 9.1) on the 50–70% of lawns on which fertilizer is used [18].

Table 9.1 Comparative fertilizer application rates in Maryland (lb ac^{-1} $year^{-1}$)[a] [17]

	Home lawn (do it yourself)	Home (lawn service)	Golf fairway	Golf greens	Cropland (corn/soybean rotation)
Nitrogen	44–261	194–258	150	213	184
Phosphorus	15	no data	88	44	80

[a] Multiply by 1.12 to obtain kg ha^{-1} $year^{-1}$

Box 9.2: The Haber-Bosch Process

In 1995, globally, 100 Tg N was "fixed," i.e., transformed from inert atmospheric N_2 to ammonia (NH_3), a form of reactive N, by the Haber-Bosch process, of which about 86 Tg was used for fertilizer. Less than 100 years prior to this, no nitrogen was thus transformed. The 100 Tg N represents about two-thirds of the entire amount of anthropogenic N in the global N cycle (the emission of N from fossil fuel combustion and associated oxidation of atmospheric of N accounts for another 25 TG) and is roughly the same as the modern estimate of N fixation by all natural ecosystems globally. The modern global nitrogen cycle has thus been transformed primarily due to a single industrial process: Haber-Bosch ammonia synthesis. The fundamental chemical reaction involved is the combination of atmospheric nitrogen (N_2) with hydrogen to yield ammonia:

$$N_2 + 3\,H_2 \leftrightarrow 2NH_3$$

This is accomplished at high temperature and pressure in the presence of a metallic (iron or ruthenium) catalyst in order to increase production rates. In addition to atmospheric nitrogen, the required hydrogen is typically produced by reacting water with methane from natural gas. Coal gasification is also sometimes used as a methane source. Thus, the Haber-Bosch process is also a consumer of fossil fuels, both as an energy source and a feedstock.

References: [19, 20]

Atmospheric deposition of N is the result of emissions of N from combustion sources, such as power stations and other industrial sources, and from automobile combustion, released to the atmosphere. Because of the relative density of such sources in urban areas, atmospheric N deposition can be relatively high in heavily populated areas. N deposition can occur either in dissolved form in rain or snow ("wet deposition") or simply attached to settling dust particles ("dry deposition"). The high temperatures of combustion processes of the emission sources transform the chemically inert form of atmospheric nitrogen gas (N_2) into other gaseous forms (e.g., oxidized nitrogen, NO_x) and ultimately into forms of "reactive nitrogen" (Nr) that include nitrate, ammonium, and many other chemical species that are readily taken up by plants and soil microbes. (One of the oxidized forms, nitric acid, can be a major component of acid rain.) Because of the concentration of these sources of combustion in urban areas, more nitrogen falls out of the sky in urban areas than in other regions. This atmospheric contribution to available (or excess) N is exacerbated by cities with large foodsheds which require long-distance transport of food (i.e., increased "food miles" from food production areas to markets), resulting in transport-related atmospheric N emissions. A recent study [21] focusing on Stockholm, Sweden, showed that the fuel energy cost of transport per kg of food delivered ranged from 0.9 to 11 Mj/kg (i.e., 1 gallon of fuel may transport 26 pounds of meat or 300 pounds of bread from the local foodshed), with atmospheric emissions varying proportionately. In the United States, the average delivery distance for food commodities is 1640 km, varying by food groups from beverages (330 km) to red meat (1800 km) [22], which is the equivalent of several kg of NO_x emissions per vehicle, assuming diesel trucks are used in transport [23].

9.3.2 Phosphorus

Unlike nitrogen, phosphorus is derived from the P-bearing minerals in the Earth's crust [24]. The natural P cycle involves rock weathering, which can yield PO_4^- ions (phosphate) as phosphorus-bearing minerals are eroded. Other than the small amount that can be carried in dust, there is no atmospheric component of the phosphorus cycle. Plants take up P from the soil as an essential nutrient, and it is consumed in organic form by other organisms. In organisms, P is an essential nutrient because it is a component of DNA molecules, phospholipid structures in cell membranes, bones, and teeth. Unlike NO_3^- (nitrate), the major form of dissolved N, which is highly mobile and moves readily through the environment, dissolved P can be adsorbed to soil particles and so moves slowly through soil. In rivers, P moves in both dissolved form and adsorbed onto sediment as it is transported by rivers.

The major anthropogenic sources of P in the modern P cycle are associated with mining of P-rich rock for fertilizer, a finite resource like fossil fuels. The development of P fertilizer extraction as an industry in the twentieth century and the widespread use of P fertilizer in commercial agriculture represented a major transformation of the global P cycle.

As with N, most of the P flowing to urban centers is in food. The average American consumes around 1 kg P per year in food. This provides the dominant load of P to the waste stream from urban areas, with additional contributions from the P content of soaps, detergents, and other nonfood sources. P fertilizer is used in urban, and especially suburban, parks, lawns, and golf courses, where levels of fertilization can match or exceed those in croplands (Table 9.1).

9.3.3 Silicon

Most people are not familiar with the element silicon (Si) as a nutrient, thinking of its use as the basic material of computer chips, but it is critically important in the world's terrestrial, aquatic, and marine ecosystems for the growth of a category of organisms which use it as a skeletal building block: the microscopic diatoms (algae), radiolarians, and other plants at the base of many aquatic food chains. SiO_2 (silicate) and other dissolved forms of silica (DSi) are major constituents of the dissolved inorganic material found in most riverine waters, ultimately derived from chemical weathering of rocks and "biogenic silica" (BSi), such as phytoliths in grasses, diatom skeletons, etc. Particulate Si (PSi) includes the mineral particles of BSi and siliceous grains of soil and rock and represents about 90% of the silica borne by rivers globally [25]. Because diatoms, which require DSi to thrive, represent a generally benign group of algae and produce high amounts of essential fatty acids, they are excellent food for the tiny aquatic animals called zooplankton. In turn, diatom-consuming zooplankton are nutritionally superior food for young fish as they grow and develop. Thus, aquatic environments with a relatively high concentration of DSi relative to other nutrients (e.g., N) tend to support productive aquatic food chains. Waters in which the DSi:DIN (dissolved inorganic nitrogen, the sum of nitrite (NO_2), nitrate (NO_3), and ammonia (NH_3)) ratio falls too low can be dominated by other algal species with undesirable characteristics, including toxic compounds potentially harmful to human health.

How are Si dynamics affected by cities? Si appears to be positively correlated with the percentage of urban area in a watershed [26]. Whether this is due to the loss of forests, grassland, and other vegetated land cover that can act as a sink of Si (uptake by plants) or to an increase in urban sources of Si is less clear. Si is a constituent of some detergents, and Si compounds are used in some industrial processes, such as paper manufacture, and these sources would likely increase in urban areas. In some cases, Si is even added to drinking water, as fluorosilicic acid or sodium fluorosilicate, during the fluoridation process. A French study suggests an approximate loading of 1 g of Si per person per day in urban settings, which may affect the prevalence of desirable or undesirable algae in local waters [27]. The Si cycle is probably affected less by human activities in cities than the N cycle, but because many cities lie along or near water bodies, small changes may have large impacts on local aquatic DSi:DIN ratios.

9.4 Technology, Transport, and the Evolution of Cities and Their Foodsheds

The nature of population centers has changed significantly over the last few centuries and most dramatically in the last 100 years or so. Old cities have expanded outward from their original boundaries as their populations swelled, building new structures on top of old ones. Relatively young cities, like most of those in the Americas, experienced the same expansion in a compressed time frame of a few centuries or even less time in Oceania and parts of Asia. At early stages of their development, population centers were villages in which productive cropland and livestock grazing areas overlapped human living quarters. The demand for food was met largely by production within village boundaries, as may be true in small farming communities in many parts of the world today. In villages, nutrient loads were relatively low because population density was low. Prior to the Industrial Revolution, the emissions associated with modern technology (centralized power stations, internal combustion engines) were largely nonexistent. As population centers became dense with human activity, often in response to technological innovations and increased trade, the foodshed of the town expanded to well beyond its borders. The result was a demand for food imports to the city and a resulting increase in nutrients in the waste stream which could quickly exceed the capacity for assimilation.

In the case of New York City (NYC), the catalyst for this growth was the development of the Erie Canal and other canal systems connecting this coastal city to inland waters and facilitating an explosive growth in NYC as a trade center during the period of westward expansion of agriculture and industry in the United States. As time went on, railroads replaced the canal system, increasing the magnitude of trade flows and making possible rapid provisioning of food and other commodities to the city from increasingly distant sources. Today, railroad transport has been supplemented or replaced by trucking and air freight. Over each period of newly exploited energy sources, the city has grown. NYC's boundaries have expanded, and the suburban regions of the metropolitan area have supplanted thousands of km^2 of land formerly in agricultural production. Its population is no longer constrained by local food production; other constraints, such as availability of potable water supplies and removal of the ever-increasing waste stream, have come into play and required their own technological innovations.

In contrast, the city of Paris, France, began as an inland town on the Seine in a relatively fertile region. Over the last 1000 years, it has grown from a town of a few thousand to a major city of ten million, with very high food demand and thus very high nitrogen and phosphorus demand (Fig. 9.1b). Though Paris has experienced the same technological improvements in transportation as New York, much of its food is still produced within the Seine basin, the local watershed of Paris, which is a largely agricultural landscape of very high fertility and productivity (Fig. 9.1a). The balance of agricultural supply and demand for food can be expressed as the ratio of autotrophy to heterotrophy (Fig. 9.1c). The Paris foodshed is consequently smaller than that of New York because of the difference in their historical development and relative richness of the local landscape.

In both cases, these cities concentrate large transfers of nutrients in food originating from regions beyond city boundaries. The resulting waste stream is channeled to receiving waters after varying degrees of treatment. In spite of municipal waste treatment, today cities represent a major, concentrated source of nutrient pollution to rivers and coastal waters. The croplands of their foodsheds, whether distributed over the globe or located in the same region, often also provide sources of nutrients to the environment, due to the excess of nutrients supplied beyond crop nutrient demand in modern industrialized agricultural systems.

9.5 Contrast Between Urban and Agricultural Regions

The bar charts on the left of Fig. 9.2a, b show the rates of inputs of N (9.2a) and P (9.2b) averaged over the top ten counties of the United States ranked by density of urban land area. These counties represent major urban centers of the United States including New York; Washington, D.C.; San Francisco; Baltimore; and Philadelphia. In these large cities, both N and P inputs are dominated by the demand of food by

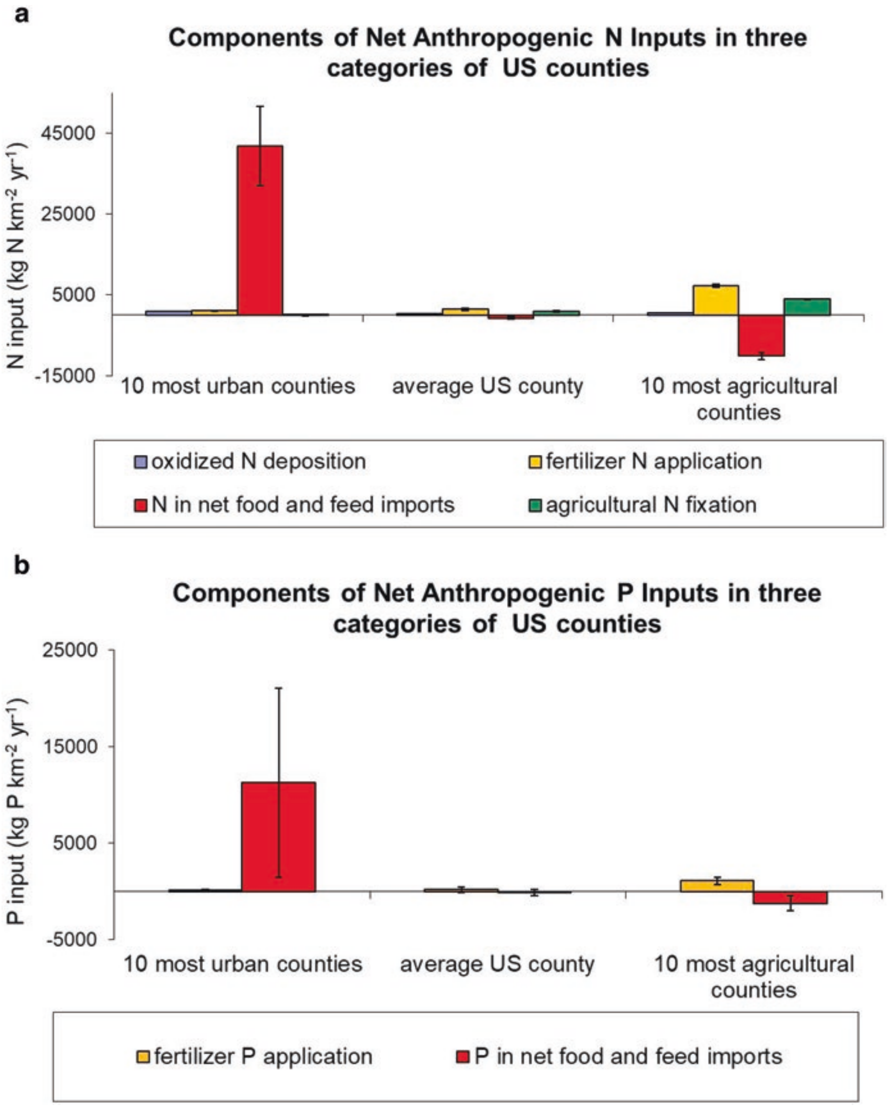

Fig. 9.2 Major inputs of nutrients to urban, agricultural, and "average" US counties. (**a**) Nitrogen; (**b**) phosphorus. In predominantly urban regions, net anthropogenic nutrient inputs are dominated by the nutrients imported in food required to meet human nutritional requirements. Land use data is from the 2001 National Land Cover Dataset (NLCD 2001; http://www.epa.gov/mrlc/nlcd-2001.html). "Urban" land area includes the following 2001 NLCD classes: "Developed, Open Space," "Developed, Low Intensity," "Developed, Medium Intensity," and "Developed, High Intensity." Agricultural land includes "Pasture/Hay" and "Cultivated Crops"

the cities' inhabitants: nutrients in food far exceed other potential inputs like fertilizer or atmospheric deposition.

In contrast, the corresponding average nutrient inputs for the top ten counties ranked in terms of agricultural land area percentage are shown in the bar charts on the right of Fig. 9.2. Here, a very different picture emerges. Farmlands require fertilizer to meet the demands of crops. Some crops, such as soybeans, are capable of fixing nitrogen directly from atmospheric N_2 and so provide a second source of N inputs. In turn, these regions export nutrients in harvested grains and vegetables, resulting in a loss of nitrogen in "net food and livestock feed" (a negative value on the figures). Effectively, fertilizer and other "fixed" N is transformed into food which is exported from regions of agricultural production and then imported to urban centers. This spatial transfer of nutrients represents a fundamental transformation of nutrient cycles in the landscape associated with the development and growth of cities.

9.6 Urban Infrastructure, Hydrology, and Nutrients

A good rule of thumb is "if it affects the water cycle, it affects nutrient cycles." Urban environments represent the most engineered landscapes on earth and therefore are the most radically altered from their pre-settlement conditions [28]. Urban areas represent the highest density of impervious surfaces of all land use categories, including paved surfaces (roads, sidewalks, parking lots) and the footprints of buildings. Beneath the impervious surface, in the city soil and bedrock, lies a network of electrical and communication lines, subway tunnels, and most importantly urban runoff drainage and sewer systems to facilitate water and waste movement to the traditional delivery points of these flows: rivers, estuaries, and other water bodies. In most cities, sewage and city runoff are combined to reduce cost. During dry periods, the combined flows can be accommodated by municipal wastewater treatment plants (WWTPs), assuring at least some level of pathogen and nutrient removal before being discharged in waterways. In high flow periods following intense storm events, much of the flow bypasses WWTPs and is discharged with little or no treatment. Here, the hope is that "the solution to pollution is dilution" due to the relatively large volume of storm flow, but the result is far from ideal. Modern sewage designs separate these flows from street drainage, thereby providing better treatment and higher levels of water quality, but leakage from aging sewage systems into urban streams can still result in pollutant discharges, especially in high flow periods [29].

Unless severely compacted from heavy foot traffic and other uses, urban and suburban lawns typically represent highly permeable areas which retain water (and nutrients) like a sponge. In contrast to the response of pavement, the runoff from lawns typically occurs only during or following intense rainfall (or irrigation) events in which water is applied in excess of the rate of saturated conductivity (infiltration capacity) of the soil. Also, in contrast to paved surfaces, grassy surfaces trap dust and other debris that would be transported readily in street runoff, so that lawns can function well as nutrient traps. Turfgrass often retains water very well compared to impervious surfaces, and nutrient loads from these sources can be managed by reducing fertilizer applications and timing irrigation to periods of low rainfall.

While lawns can trap materials, they also have relatively high rates of nutrient inputs, primarily as fertilizer application (Table 9.1), but also due to atmospheric deposition of nitrogen, especially in areas of high emission sources (e.g., high automobile densities), which may overwhelm their ability to hold nutrients.

Streets and other paved surfaces accumulate nutrients from atmospheric deposition, from garbage and litter, and from animal wastes. Prior to the development of the automobile, transportation in urban regions depended on horses and other draft animals. The gutters of urban streets were awash in manure and its associated nutrient load, to such an extent that enterprises developed to collect and sell the material as fertilizer [30]. Today, the nutrient load from animal sources in cities is much lower than it was in the late 1800s. Modern animal sources of nutrients include pets and city “wildlife” (pigeons and rats come to mind, but also many other organisms that owe their existence to nutrient subsidies from human activities). Some estimates of the nutrient loads from the urban pet population suggest that it is not a negligible fraction of the human waste stream. A mass balance of the Central Arizona-Phoenix urban system [31] estimates nitrogen inputs of pet food to the urban ecosystem at about 27% that of human food. How much pet waste ends up in the solid waste stream vs. street runoff is an open question.

Even assuming that sewage flows are separated from stormwater runoff, high flow rates during storms result in a higher capacity to transport sediments of all kinds, so that the impervious nature of the city surface ensures more transport of street debris to receiving waters from paved surfaces than from porous ones. Modern cities design their stormwater management systems to include retention and settling basins and other features to slow water flow and trap debris. Because the urban hydrological system moves water faster than corresponding regions with lower pavement density, materials carried in the urban flows in suspended or dissolved form have less time to be “processed” into forms that can be assimilated by plants and soil microbial activity. The more efficient delivery of materials results in an even higher load to receiving waters than from regions with less impervious surface [32].

9.7 Sewage Systems and Waste Treatment

As of 2000, 84% of the world’s urban dwellers were served by a sewage system, in which waste can be collected and treated to remove nutrients to varying degrees [33]. Prior to 1875, there were no facilities to treat municipal sewage in the United States [34]. While many of the urban populations of developing countries still have little or no sewage treatment, in the United States and other developed countries, most urban areas have had sewage systems and waste treatment facilities in place for over half a century, though the quality of treatment varies widely. Primary treatment essentially involves allowing solids to settle before discharging liquid effluent

Table 9.2 Typical composition of untreated domestic wastewater (concentration data from [35])

	Concentration (mg l^{-1})			
Contaminants	Weak[a]	Medium[b]	Strong[c]	Per capita load (kg $person^{-1}$ $year^{-1}$)
Total solids (TS)	390	720	1230	107–121
Total dissolved solid (TDS)	270	500	860	74–84
Suspended solids (SS)	120	210	400	33–35
Total organic carbon (TOC)	80	140	260	22–24
Total nitrogen (as N)	20	40	70	5.5–6.7
Organic nitrogen (as N)	8	15	25	2.2–2.5
Ammonium (as N)	12	25	45	3.3–4.2
Nitrite (as N)	0	0	0	0
Nitrate (as N)	0	0	0	0
Total phosphorus (as P)	4	7	14	1.1–1.2
Organic P	1	2	4	0.3–0.4
Inorganic phosphate (as P)	3	5	10	0.8–0.9

[a] Estimate for wastewater flow rate of 750 l $person^{-1}$ day^{-1}
[b] Estimate for wastewater flow rate of 460 l $person^{-1}$ day^{-1}
[c] Estimate for wastewater flow rate of 240 l $person^{-1}$ day^{-1}

to receiving water bodies, with minimal removal of nutrients. Secondary treatment involves controlled breakdown of organic matter and other materials (human waste, food waste, soaps and detergents) by natural activity of decomposer microbes. Most waste treatment plants rely on aerobic biological processes, requiring aeration of the effluent in holding ponds. The aim of this process is to reduce the "biological oxygen demand" (BOD) of sewage effluent so that the oxygen levels of receiving waters can be maintained when the effluent is discharged. Tertiary treatment includes any additional processes beyond secondary treatment and is aimed at further increasing the effluent quality before it is discharged, typically by filtering flocculent organic material, chemically or biologically removing P from the effluent, or biologically removing N from the effluent using biological nitrification/denitrification processes. Thus, the effluent from municipal sewage treatment facilities carries much of the original dissolved N and P in the waste stream of the city unless tertiary nutrient removal methods are employed (Table 9.2). For the minority of urban wastewater treatment facilities that do provide tertiary treatment, wastewater nutrient loads are significantly lower and can also be lower per capita than many on-site wastewater systems typical of rural areas.

9.8 Conclusions

Urban regions differ from other areas affected by humans (e.g., agriculturally dominated regions) and relatively unimpacted regions, specifically with respect to nutrients, by virtue of their concentration of human activity. Urban areas experience large inputs of N and P in several forms, including nutrients embodied in foods consumed by their human populations, as well as fertilizer inputs to lawns and other

Table 9.3 National median concentrations (mg/l) of nutrients and other pollutants in urban stormwater [36]

Constituent	Concentration (mg l^{-1})
Total suspended solids	54.5
Total phosphorus	0.26
Soluble phosphorus	0.10
Total nitrogen	2.0
Total Kjeldahl nitrogen	1.47
Nitrite + nitrate	0.53

areas, and sources of atmospheric N associated with combustion. This concentration of nutrients is fundamental to the nature of cities and is why they play such a major role in regional nutrient budgets and water quality impacts (e.g., eutrophication and hypoxia) on local and regional waters.

Nutrient flows in runoff from urban and suburban areas following rain or snowmelt exhibit increased concentrations of both phosphorus and nitrogen, which further enrich the nutrient loads to rivers, lakes, estuaries, and other receiving waters, thereby increasing their level of eutrophication (Table 9.3). Changing climate scenarios suggesting intensification of storms in some urban areas may exacerbate nutrient losses as well [37]. Sources of N and P in runoff water from urban sources can include fertilizer from lawns and other areas, atmospheric deposition (mainly N), animal waste, and organic nutrients from garbage, lawn clippings, and other debris. Leakage from sewage lines and septic systems also represents potential sources of N and P in urban and suburban runoff [29, 38]. Thus, the effluent of nutrients in runoff and sewage is likely to remain a fundamental feature of cities.

The ultimate source of most of the nitrogen in cities is nitrogen fixed by industrial fertilizer factories supporting food demand and other uses or as by-products of fossil fuel combustion. Both of these sources are energy-intensive and thus tied to our energy future and climate change. In contrast, most of the fertilizer phosphorus used on crops and lawns is mined and thus nonrenewable on human time scales. In the centuries to come, this may prove to be the limiting factor on crop production and thus the flow of phosphorus in food to cities.

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Chapter 10
Material Cycles

Brandon K. Winfrey and Patrick Kangas

Abstract Material cycles in urban systems are strongly influenced by human-driven activities. Similar to ecosystems, which form via production processes that use material and energy as inputs, urban areas require materials for industrial production. By coupling processes of constructive production and regenerative breakdown, materials can be cycled sustainably in cities. Waste materials are generated when no more utility can be derived from that material. In urban areas, recycling materials plays an important role in maximizing the amount of utility that can be derived from materials flowing into the city, which is evidenced by the increasing trend of recycling certain materials in solid municipal waste management and electronic components.

Keywords Solid waste · Recycling · Urban metabolism · Industrial ecology · Emergy

10.1 Material Flows and Cycles

Material flows are an important part of all ecosystems, from the smallest microcosm to the biosphere as a whole. As inputs to production processes, materials enable the development of ecosystem structure and metabolism. Thus, for example, carbon, nitrogen, and phosphorus are required for biomass production in photosynthesis. Likewise, in human-dominated ecosystems, materials are required for industrial

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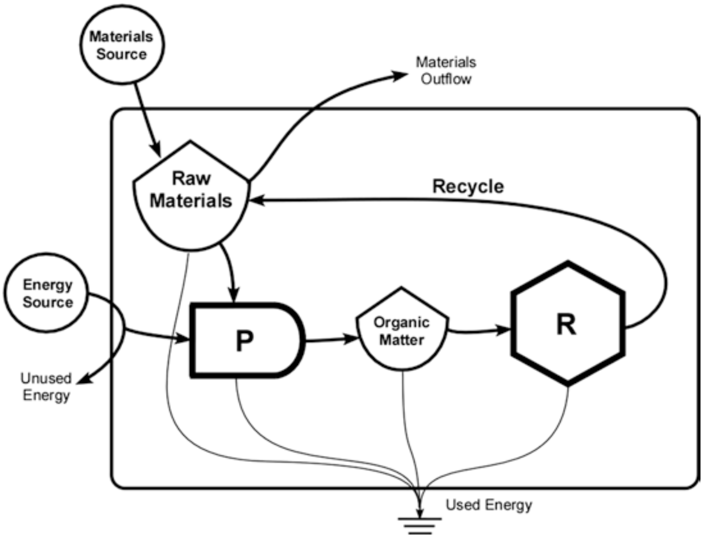

Fig. 10.1 Generalized model of the ecosystem showing the balance between production and consumption and the cycling of materials

production. For example, calcium carbonate, iron ore, and coal are required inputs for steel production. Sustainable material flows require cycling which results from coupled processes of constructive production and regenerative breakdown. The classic example of this coupling is the P-R (production-respiration) model from ecology (Fig. 10.1). Normally, respiration is used to describe the chemical process common to all organisms whereby their cells obtain energy by combining oxygen and glucose (the product of production). This results in the release of carbon dioxide, water, and ATP (the currency of energy in cells), but here, it is used to signify consumption at the ecosystem level, the opposite of production.

The model in Fig. 10.1 uses the energy circuit language to depict the essential processes and storages in an ecosystem [1]. This is a symbolic modeling language in which different shaped symbols represent different kinds of system components and processes. The lines represent flows of energy or material, the tanks represent storages, the circles represent sources outside of the system, and the large bullet-shaped symbol and the hexagon represent the composite functions of production and consumption, respectively. In the model, organic matter (or biomass) is produced by interacting solar energy and raw materials during photosynthesis (which is termed primary production in ecology). It is subsequently broken down in consumption, or respiration, and the raw materials are recycled to their storage. Energy flows into the system and then out through the drain at the bottom of the diagram which is termed a heat sink. This kind of highly aggregated model is called a P-R model because it depicts the coupled processes of primary production (P) and community respiration (R). Materials such as the carbon and the nutrient elements of nitrogen and phosphorus cycle in the system as a consequence of the coupled P and R. When the processes are balanced (P = R), then the materials can cycle sustainably.

Performance of systems is dependent on balancing the amounts in storages and the rates at which the storages are produced by production processes or released by consumption processes. Limits to performance occur when some part of the cycle is constricted. In ecology, those storages of materials that are too small to maintain processes are termed limiting factors. Processes (rather than storages) themselves can limit performance, and these will receive attention in this chapter.

The real-world system on which the P-R model in its idealized form is based is the open ocean plankton system studied by Alfred Redfield [2–4]. In the open ocean far from land, the plankton exists essentially as a closed system with phytoplankton producing biomass from uptake of carbon, nitrogen, and phosphorus plus sunlight and zooplankton and other microconsumers breaking down the biomass and releasing the carbon, nitrogen, and phosphorus back into seawater. Redfield discovered the plankton organisms are composed of carbon, nitrogen, and phosphorus in the same ratio as occurs in seawater, and he deduced that the material cycle was balanced. Thus, no individual element is limiting but rather all elements together are limiting. Under these conditions, there is no waste, because the plankton system was able to evolve the material flows from productive uptake and regenerative release so that a perfect material cycle emerged.

This was the dogma of biological oceanography of the 1950s, and it made for a great story. One wonders if Redfield had added iron to the seawater, as in the more recent IRONEX work, would he have increased production and thus revealed a limiting factor for the plankton [5]?

In any case, it seems clear that many ecosystems are evolving toward a balanced material cycle, even if few or none have actually achieved it. Certainly, most ecosystems have blockages at some point in their cycles that reduce metabolism. A good example of this kind of blockage occurred in the Carboniferous Age when land plants evolved faster than their decomposers and biomass accumulated in the swamps, which later converted to coal. The blockage was the rate of decomposition. The story of oil accumulation is similar, with phytoplankton evolution outpacing the evolution of their decomposers. Thus, all of the fossil fuel deposits are evidence of unbalanced material cycles where P > R. In these cases, the process of regenerative recycle limited ecosystem metabolism, which is also the case in modern human-based ecosystems. Over geologic time though, the evolution of decomposers has caught up with producers such that fossil fuels are being produced at tiny rates that are much slower than those of our geologic past.

The beautiful nutrient cycles illustrated in introductory ecology textbooks give the impression of perfect cycles. Blockages and limiting factors occur in all natural material cycles (except perhaps for Redfield's open ocean plankton). In reality, because at least portions of these cycles are living organisms, the cycles are always evolving toward a perfectly balanced organization of flows and storages. In natural ecosystems, the cycles themselves emerge from the individualistic behavior of living and nonliving components at each step over evolutionary time, and they are the subject matter of the field of biogeochemistry. Human-dominated ecosystems such

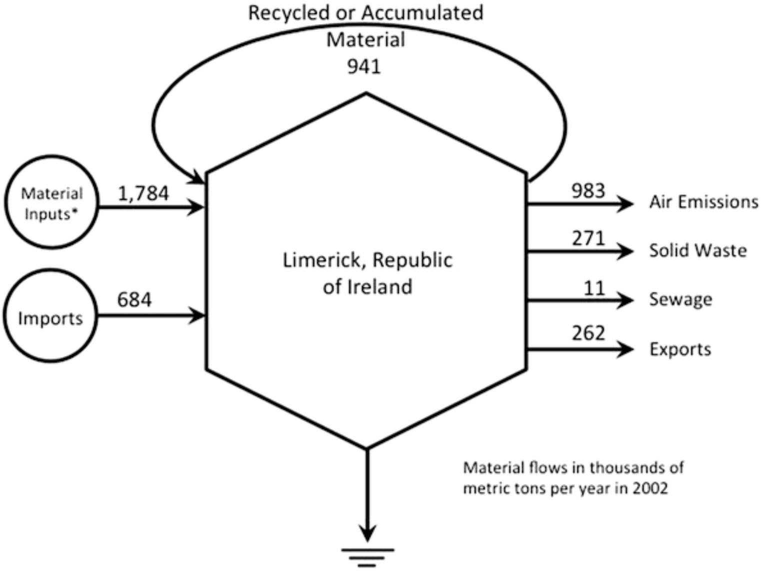

Fig. 10.2 Material flows for the city of Limerick, Republic of Ireland, represented in thousands of metric tons per year for the year 2002 [6]. *Material inputs include food, fuel, consumer goods, and raw materials used in production

as cities are similar with consumer demand for products (inputs, Fig. 10.2) and solid wastes (outputs, Fig. 10.2). While economics determine the inflows and outflows from cities, cultural factors are also important in controlling the consumptive demand for the inflows [7, 8]. In general, material inflows to cities are proportional to urban populations with adjustment for levels of wealth. In addition, material inflows concentrate in cities due to their function as centers for government, industry, and corporate headquarters (see Chap. 5) and due to their role as regional trade centers. These high material inflows to cities require effective methods of internal distribution and use, but when products reach their end of life, disposal and recycling become critical functions that must be carried out in cities. In this paper, emphasis is given to the output portion of urban material flows, which is technology based.

10.2 The Concept of Waste and Its Role in Urban Material Cycles

Before moving into the realm of human systems, it is useful to explore the concept of waste from a general systems perspective. The basic unit of material cycles is the production process shown in Fig. 10.3 with the workgate symbol from the energy circuit language. In this diagram, several inputs interact in the workgate symbol to

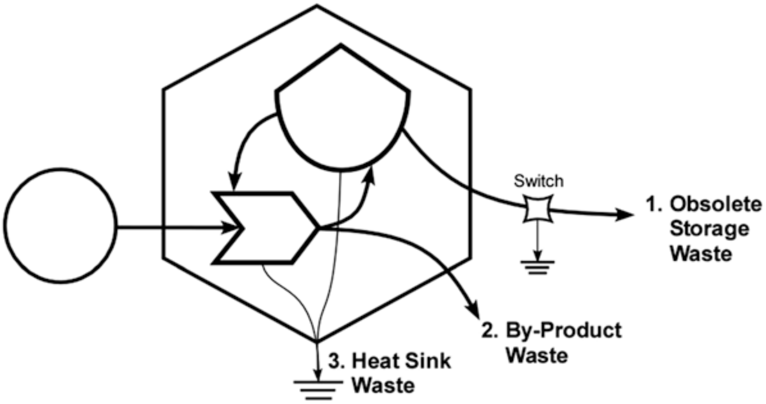

Fig. 10.3 Energy circuit diagram for defining wastes

produce a storage of material. The flow from the workgate to the storage is the intended flow of energy or material that is the objective of the production process. Also shown are flows leaving the workgate as by-products and as heat. These are unintended flows from the perspective of the production process. In a living population, the flow to the storage would be the accumulation of biomass through growth, while the flows as by-products and heat would be waste products from excretion and from metabolism, respectively. Through evolution, natural selection will tend to minimize the amount of energy and materials lost to by-products so that the largest flow is available for growth and reproduction of the population. While the by-products and heat can be minimized, they cannot physically be eliminated. The loss of heat is an inevitable consequence of the second law of thermodynamics, and, since heat is the lowest quality of energy, it has little or no utility, and it is dissipated into the global heat budget. The by-products of the production process, however, contain some free energy, and thus they can have utility to an upstream system with adaptation to utilize the flow to drive another production process. If no upstream system is available to utilize the by-product, then problems can arise. At best, the by-product can accumulate somewhere unused, which represents lost potential energy (as storage). At worst, the by-product can act as a pollutant that can stress other parts of the overall system. In either outcome, the by-product is waste because it is not utilized productively.

In cities, inflowing materials include fuels, food, building materials, consumer goods, atmospheric deposition, water, and living organisms, which are all utilized on varying time scales and cycled within the city to produce outputs such as information, goods, and services. While some inputs leave cities with minor changes in utility (usefulness), such as humans coming and going, most material inputs lose nearly all utility after leaving cities (e.g., fuel and food) and become wastes (e.g., air and water pollution). Other materials flowing into cities remain there on much longer time scales and continue to reinforce feedback loops that contribute to utility throughout their lifetime (e.g., building materials used to construct skyscrapers), but require considerable resources to remove at the end of their useful life. Still other material inputs to cities, like consumer goods and food packaging, lose nearly all utility within the city, while the material itself remains relatively unchanged, representing an opportunity for recycling raw materials that has become economically advantageous, as evidenced from bottle deposits and recycling centers that collect glass, aluminum, cardboard, and plastic.

In the short run, waste is an unavoidable consequence of a production process, but, as long as the system is capable of evolution, in the long run, the waste can be converted into a positive contribution. Volk and others have described how this evolutionary process is at the basis of the entire biosphere with the Gaia model [9–11]. He suggested that the history of the biosphere has been a "wasteworld of by-products" in which unintended by-products of metabolism have led to the diversification of the biosphere. Thus, new species that utilize the by-products of existing species are continually evolving, driving the biosphere at different scales toward the perfect nutrient cycles of the type Redfield envisioned for the open ocean. A good example from the history of the biosphere is what occurred when photosynthesis first evolved. Oxygen is a by-product of photosynthesis, and it was a toxic pollutant to most of the existing biodiversity of anaerobic (meaning living without air) microbes in the Precambrian Age. It took nearly a billion years of evolution from the start of photosynthesis to diversify the biosphere with aerobic microbes that in turn had much greater energy flow due to the use of oxygen as a terminal electron acceptor in aerobic versus anaerobic cellular metabolism. Thus, an aerobic biosphere emerged from the previous anaerobic biosphere when natural selection turned the waste by-product oxygen into a useful input to the production process of aerobic metabolism.

The selection pressure that turns wastes into resources has been termed the loop reinforcement principle in systems ecology [1]. This principle is illustrated in Fig. 10.4 with a comparison of producer-consumer energy circuits. The principle suggests that the consumer whose waste by-product is dispersed into the environment will be outcompeted by a consumer that can use the waste by-product to reinforce the producer. The wasteful consumer shown in Fig. 10.4a only drains energy from the producer, while the consumer shown in Fig. 10.4b rewards the producer with energy subsidy, creating a symbiotic relationship of mutual benefit. In ecosystems, an example of Fig. 10.4b is a herbivore that recycles nutrients in chemical forms and ratios that fertilize the plant species that it eats.

A final concept of waste comes from the storage in Fig. 10.3. The storage is the intended outcome of the production process, but it becomes a waste if it is not used and recycled at an appropriate frequency. The flows leaving the storage must equal the incoming flows for a steady state to exist. Long-term net production greater than use can result in a kind of "oversupply" of the storage, which can limit material cycling through blockage. H. T. Odum suggested that in these cases, systems may develop a pulse that recycles the excess storage [12].

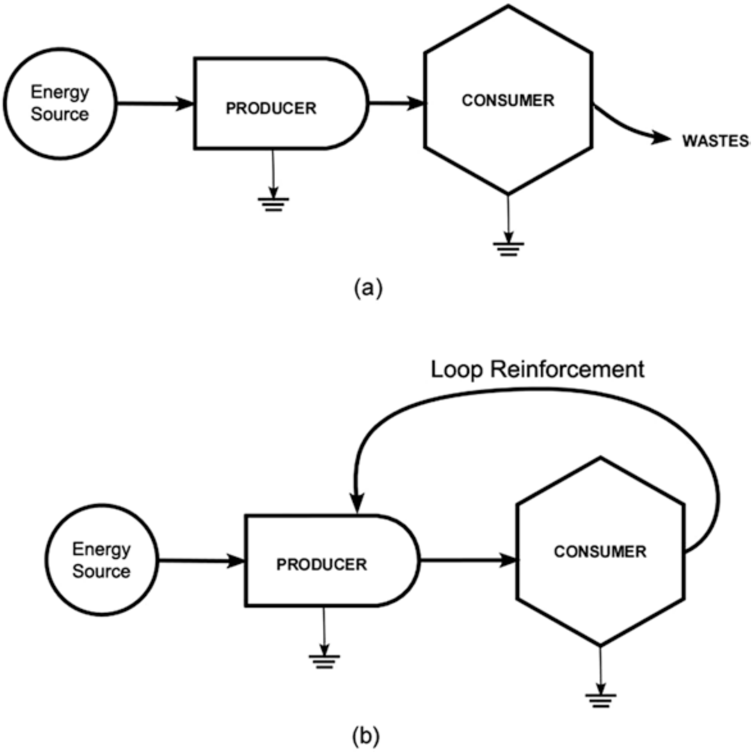

Fig. 10.4 Comparison of producer-consumer circuits (**a**) without and (**b**) with loop reinforcement

10.3 Industrial Ecology

Industrial ecology is an exciting new field that studies material flows in human systems. In this field, ecology is used as a model for understanding and designing use and disposal of materials in human systems. While industrial ecology may seem to be an oxymoronic term, it may be a good example of the kind of interdisciplinary perspective that is needed to solve modern problems [13]. The intention of the field is to improve the performance of human systems by making material use more effective and by reducing impacts on natural ecosystems. According to Graedel and Allenby [14]:

> Industrial ecology is the study of the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal…

The intentions of industrial ecology outlined above may sound familiar since environmentalists have had these intentions for many years. What is special about the new field is that it originated from the efforts of industrial engineers and economists, rather than ecologists and environmental scientists. The founders of industrial ecology have little background in academic ecology, but they became inspired by the way natural ecosystems function, and they have developed new ways of thinking about and designing how industries function. Most of the concepts from ecology used by industrial ecologists are somewhat elementary, so it is a fertile discipline for traditional ecologists to contribute more sophisticated concepts and theories from the study of natural ecosystems.

Both ecology and industrial ecology are concerned with metabolism. In natural ecosystems, metabolism constitutes the combined processes of production and respiration described earlier in terms of the P-R model. In industrial ecology, studies of urban metabolism have been emphasized, and they often take the form of mass balances of inflows and outflows (Fig. 10.5) [15, 16]. These studies document the great magnitudes of materials that are processed in cities [17–19]. Unlike most natural ecosystems in which energy flow drives the cycling of materials (such as nutrients), in cities energy flow drives transformation and flow-through of materials. For example, food (material) that is a transported into the city uses fuel (energy) for the transport, storage, preparation, and finally treatment as it leaves through the wastewater treatment plant into the receiving environment outside the city. In these human systems, production and respiration are separated spatially with respiration concentrated in the cities and production distributed in the surrounding rural areas or even in distant regions for high-value materials. Cities in turn export important finished products to the rural areas. Thus, more cycling takes place between cities and rural areas than within the cities themselves.

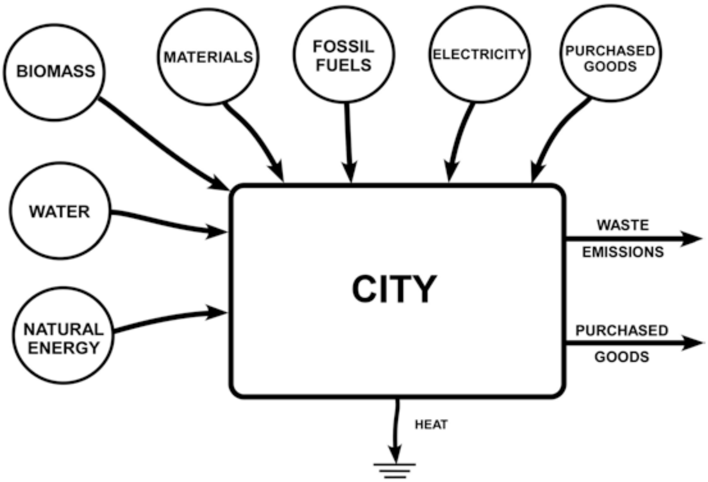

Fig. 10.5 Energy and material inflows and outflows of an urban system

Industrial ecology has a goal of achieving global sustainability; balanced material cycles are an important objective. Industrial engineers have had an interest in the supply of materials for many years as inputs to production processes with emphasis on strategic assessments [19–21]. Waste reduction and recycling of scarce materials have also been a focus for improving industrial performance for many years [22–24]. However, industrial ecology has brought a new holistic synthesis to these studies, so that flows of materials are tracked from primary sources to final disposal with attention to environmental impacts at each step.

The main tool of industrial ecology is the life cycle analysis (LCA), which is a systematic accounting of all inputs and outputs to production processes [25]. Typically, LCA is applied to a particular industry with a flow chart diagram as a model (see, e.g., ref. [26] for an analysis of the automobile). At each step in the flow chart, material and energy inputs are shown along with residue outputs (Fig. 10.6). The LCA is complete when all the inputs and outputs have been quantitatively evaluated in their own appropriate units. This accounting model can then be utilized as a planning tool to improve industrial production and to reduce environmental impacts from the use and disposal of products.

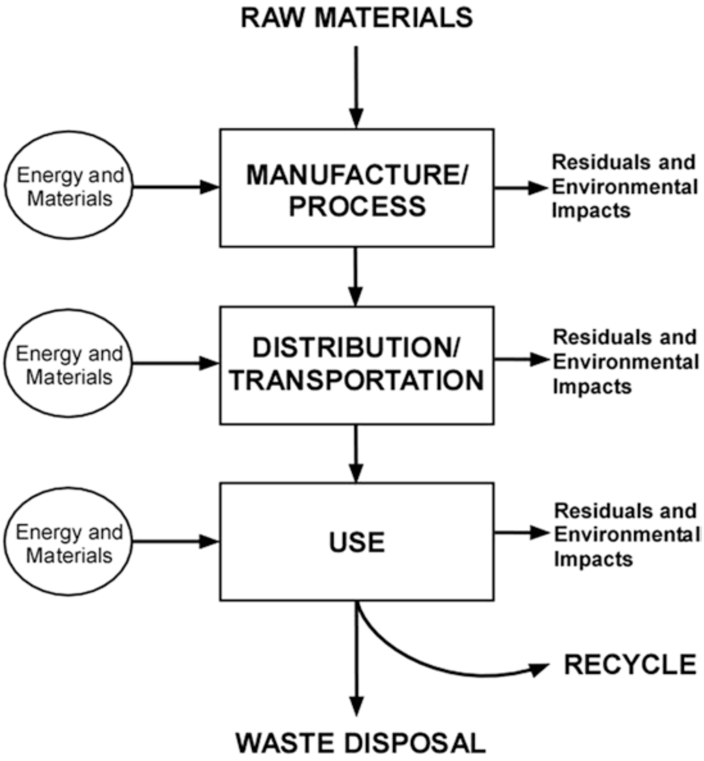

Fig. 10.6 Life cycle analysis (LCA) process flow diagram

Industrial ecology is very much a design discipline, and a good description of this dimension of the field is given by McDonough and Braungart [27]. The title of their book is *Cradle-to-Cradle* which is a metaphor for economies with balanced material cycles. The "cradle" represents the primary materials at the base of an economy and "cradle-to-cradle" represents a cycle in which at the end of the product's life, the materials it is composed of are recycled and used again to make a new product. The opposite situation is termed "cradle-to-grave" which is the condition of the present-day society. In this situation, at the end of a product's life, it is disposed of in a landfill (e.g., the "grave"), and the materials it is composed of are lost to the system and not recycled. Thus, the design of products that can be recycled and that have no environmental impact is an important part of this new field.

A goal of industrial ecology is to organize individual industries into a network in which the waste from one is a resource for another (Fig. 10.7). While this goal may seem to be an unrealistic dream, a model system has been created in Kalundborg, Denmark, through careful planning [13]. Here, several industries (a power company, a pharmaceutical plant, an aquaculture facility, and a wallboard maker) have co-located in an "ecopark" in which the industries exchange waste heat and materials, creating a network of mutual support. This kind of local-scale symbiotic industrial network may offer advantages over the present-day globalized industrial system when fossil fuels for international travel and coordination become more expensive.

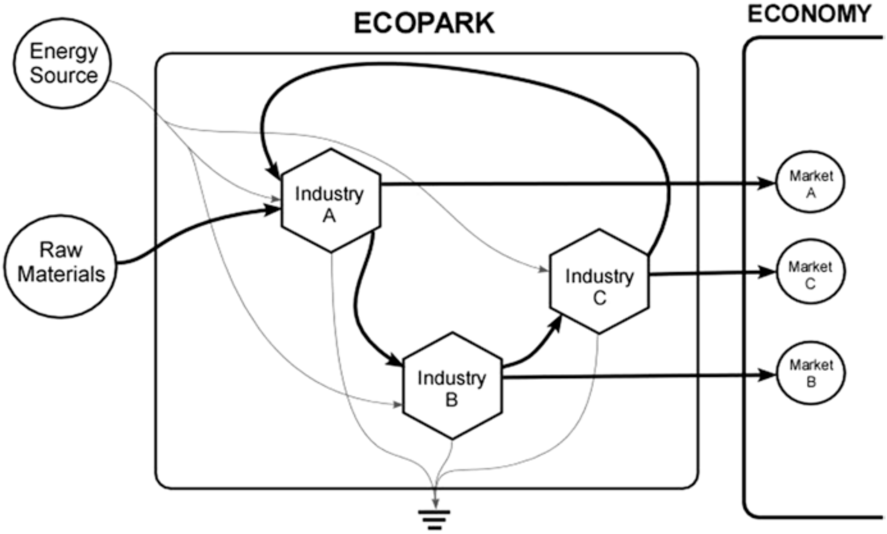

Fig. 10.7 A network of symbiotic industries

10.4 Waste Production and Management in Cities

While ideas from industrial ecology offer new approaches for dealing with human material cycles in the future, people in cities are producing solid wastes that must be managed in the present. Typical municipal solid waste is composed of four sources: residential (50% of the total), commercial (25% of the total), industrial (12.5% of the total), and institutional (12.5% of the total) [28]. On average in 2014, each person generated a waste stream of 4.4 pounds/day (2 kg/day) in the United States with the composition shown in Table 10.1 [29]. This waste material must be removed on a frequent, regular basis, or public health concerns arise, and cities would literally fill up with trash!

Methods of disposal of municipal solid waste are well-known and represent an important, profitable industry in its own right [28]. The first step is always collection and transport of waste. This step is carried out by a contracting firm that operates crews of workers and trucks that collect solid waste from designated locations throughout a city. In some cases, waste is transported and temporarily stored at transfer stations, but ultimately there are three main options for disposal: landfilling, incineration, and recycling. The landfilling option (Fig. 10.8) began historically with removing trash from cities and concentrating it in open dumps. While this approach still occurs in underdeveloped countries, the landfill has evolved in the developed world. The first stage was the sanitary landfill in which trash was dumped into pits and then covered with a soil cap. This improvement reduced contact of disease-carrying organisms with the trash, and thus, it reduced the public health threat of exposed trash. The final stage in the evolution of the landfill occurred with implementation of engineered liners plus leachate and gas collection systems, which minimized groundwater pollution and further reduced the public health threat of solid waste disposal. The advantages of the landfill option are that it is a relatively safe and inexpensive approach to disposal of municipal solid waste, in comparison to other available options such as recycling or incineration. The disadvantages are (1) increased methane emissions and (2) constraints on land availability in which to bury solid waste, especially in the vicinity of cities. This situation causes landfills to

Table 10.1 Municipal solid waste generation in the United States in 2014 (data from ref. [29])

Material	Generation (million tons)	Percent (%)
Paper	68.6	26.6
Food	38.4	14.9
Yard trimmings	34.3	13.3
Plastics	33.3	12.9
Rubber, leather, and textiles	24.5	9.5
Metals	23.2	9
Wood	16.0	6.2
Glass	11.4	4.4
Other	8.3	3.2
Total	258	100

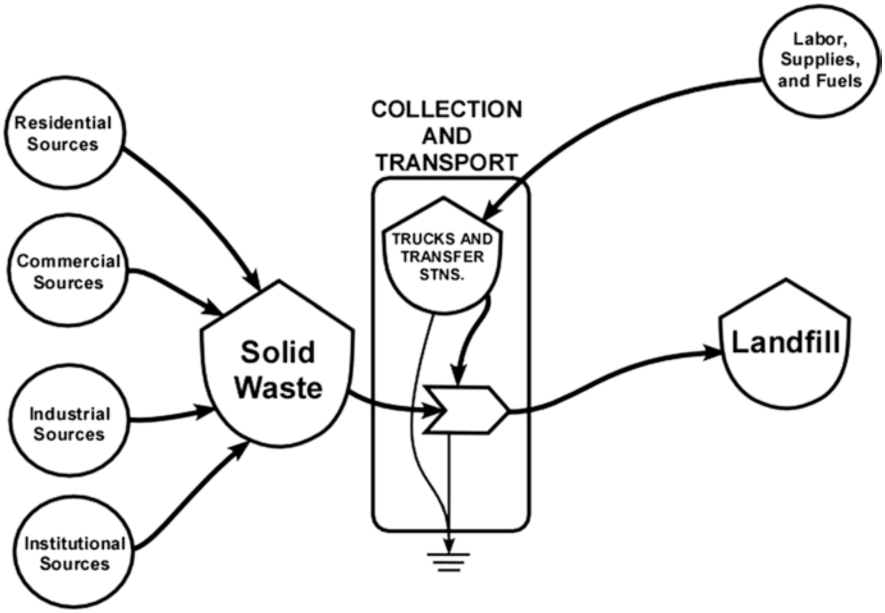

Fig. 10.8 Landfilling

be sited at increased distances from the source of trash generation, which leads to greater transportation costs and, consequently, CO_2 emissions.

Another option for solid waste disposal is incineration (Fig. 10.9). The basic attraction of this approach is that the volume of waste is reduced by a factor of 10 since the solid material is transformed by combustion into gases and fine, suspended particles called fly ash. The remaining material is termed bottom ash, and it can be sent to a landfill for final disposal. The original application of incinerators for trash disposal emitted large quantities of atmospheric pollution. However, new technologies, such as activated-carbon injectors and particle traps, have been developed to reduce these emissions. Because the heat generated by combustion of trash is a potentially useful by-product of this solid waste management option, incinerators have evolved into waste-to-energy plants. The heat is used to generate steam, which runs turbines that generate electricity. Some new variations of this approach utilize pyrolysis in which trash is converted into gas in the absence of oxygen and then into liquid fuel. The advantages of incineration and pyrolysis are that much less landfill space is required for final waste disposal and useful energy sources are produced as by-products. The disadvantages are that these waste-to-energy plants are expensive and some air pollution is emitted from the systems.

A final option for waste disposal is to recycle materials to productive reuse (Fig. 10.10). This option involves careful sorting of the waste stream into categories from which materials can be profitably reused as inputs to new production processes. This is a conceptually attractive waste management option, which leads to

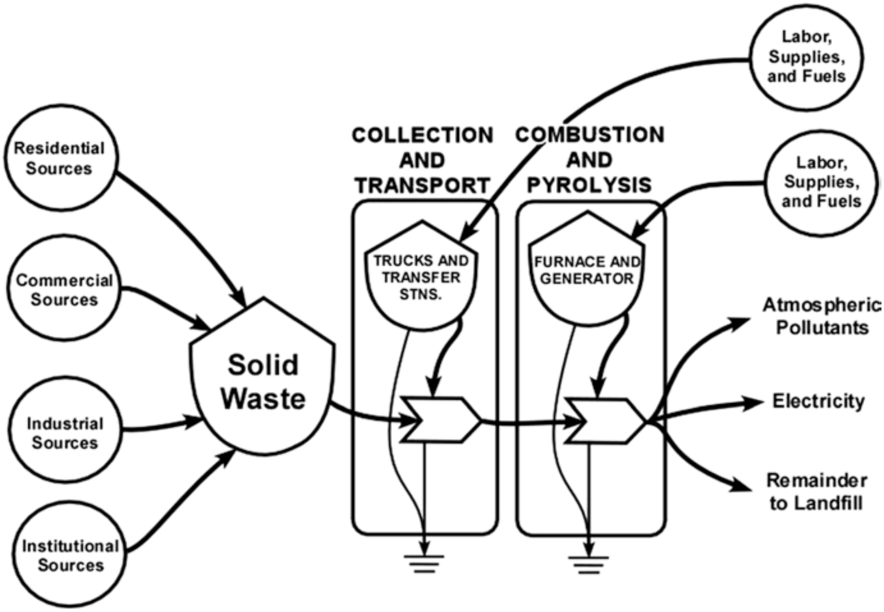

Fig. 10.9 Combustion and pyrolysis

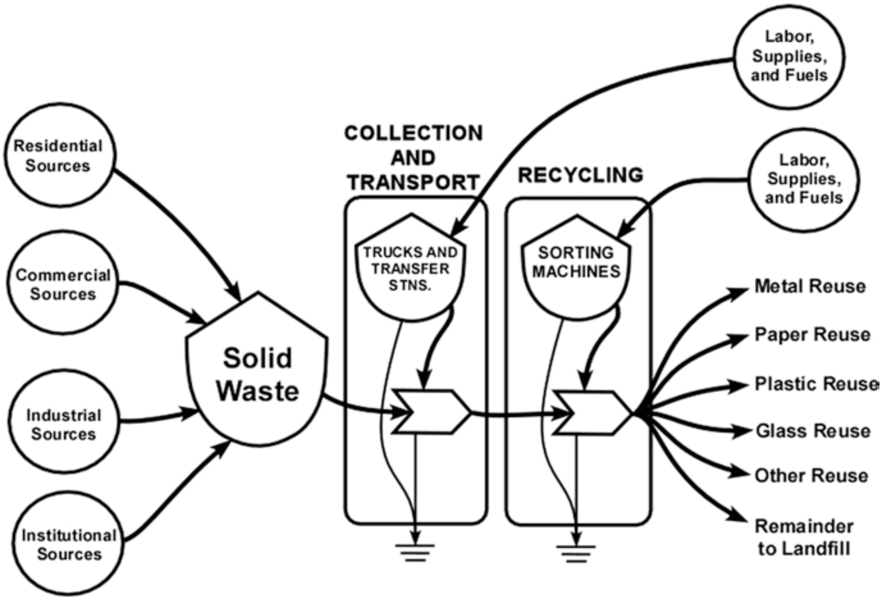

Fig. 10.10 Recycling

material cycling rather than one-way flow to dead-end disposal (e.g., “cradle-to-cradle” rather than “cradle-to-grave”). This option is most like the models from ecology in which nutrients cycle between producers and consumers (see Fig. 10.1), and thus it is a focus of industrial ecology. For recycling to occur in an ecosystem, an organism has to generate net energy by transforming the waste product and thus moving it along a material cycle. In the example mentioned earlier in the chapter, decomposer organisms that derived net energy from breakdown of the leaf and wood litter produced in Carboniferous Age swamps had to evolve before the biomass that previously had turned into fossil fuels could be consumed and the material recycled. Thus, all the cycles in ecosystems had to develop over time as decomposers evolved to take advantage of free energy available in waste products from plants and other organisms. The process is generally similar in human systems. In this context, a business has to evolve that can create a profit from recycling a waste product. There are many barriers to this kind of economic evolution, and so recycling remains limited in human systems. In North America, for example, very few communities achieve 50% waste recycle, and in 2014, in the United States, the national average was about 35% of waste recycle [29]. Overall, the advantages of recycling are that the waste stream reaching the landfill is reduced and materials are reused, contributing directly to sustainability. The disadvantages of recycling are that it is inherently limited by available technologies for reuse and it is relatively expensive in comparison to landfilling. While most metals can be recycled to their original quality, some recycled materials are less useful than in their original form (e.g., water bottles cannot be recycled to water bottles and instead become park benches). Additionally, due to the higher expense, the market for recycled materials is smaller.

Ultimately, cities’ solid waste management decisions are made based on cost of disposal, which vary significantly according to economies of scale [30]. Still, landfilling is the least expensive disposal option in the United States at $50/ton of waste. Incineration and recycling are more complicated options that are more expensive [30, 31]. However, both incineration and recycling can yield useful by-products, so the solid waste does have value if an appropriate system exists that can use the waste as input to a new production process. In fact, even waste that is buried in landfills can be thought of as having value in the long run, in the sense that the landfills could be mined for resources at some time in the future. Realizing the value of wastes is a prerequisite for designing new human-based material cycles, and an accounting system that can assess this value is discussed next.

10.5 Emergy Conceptions of Waste and Material Cycling

Waste and material in urban areas can be evaluated using various economic and environmental analysis techniques (e.g., life cycle, energy, cost-benefit, etc.). Emergy is one of these techniques; emergy analysis aims to quantify material and energy in systems using a common unit of comparison. By definition, emergy is the amount of available energy of one type used directly and indirectly to make a product or service [32]. The amount of available energy of one type embodied in a product or service is a reflection of its quality [32, 33]. When more available energy is used up in energy transformations (i.e., higher emergy), the resulting energy, while lower in energy terms, is higher in emergy and thus higher in quality. Energy quality relates to the ability to do work. Energy that has high quality is able to do more work. For example, electricity (high quality) can power a computer, while the same amount of energy, if available only in the form of photons from the Sun, cannot power a computer (i.e., 1 J of electricity can do more work than 1 J of solar energy). Many solar joules must be transformed through various production processes in order to do the same work as the 1 J of electricity (i.e., electricity has high emergy per unit energy; solar energy has low emergy per unit energy). The amount of emergy it took to make a joule of a product or service is referred to as its transformity, typically calculated in terms of solar emjoules per joule. For example, the ratio of solar emjoules (sej) used directly and indirectly to make 1 J of electricity (i.e., the transformity of electricity) is typically on the order of 10^5 sej/J, depending on the inputs to the production process.

Brown and Buranakarn used emergy analysis to evaluate material cycling in the built environment by quantifying the cost of landfilling and the recyclability of common construction materials [34]. They found that materials with high quality (according to emergy values, e.g., steel, aluminum, and cement) were recycled at higher rates than those materials with lower quality (according to emergy values, e.g., wood, plastic lumber, and clay brick). This finding indicates that materials used for structures in cities, with large amounts of emergy used to concentrate them, are advantageous to recycle due to their higher quality (i.e., higher specific emergy).

In traditional emergy analysis, the quality of a product increases only with each use (i.e., more energy is put into the product, so emergy increases). To address this concern with regard to recycled material, where the quality is not inherently increased just by reusing the materials to make a new product, Brown introduced the idea of "emformation" [35]. This principle suggests that the evaluator track separately the emergy associated with material and the emergy used in the formation of that material into a product. For instance, the emergy of an aluminum can would have the emergy of the aluminum material and the emergy involved in forming the aluminum into a can tracked separately. When recycling the can, the emergy of the aluminum material would be recycled, while the formation emergy ("emformation") would be lost. This was a novel application of emergy concepts, as emergy is not typically thought to be "lost."

Waste is the result of society's consumption of agricultural and industrial products being decoupled from natural material cycling loops [1, 36]. Urban systems are self-organizing systems, which is evident from their high resource use and production of high-quality energy (e.g., information and technology). By-products of this high resource use are energy and material flows that have no intended use downstream (e.g., wastewater and solid waste). While waste can have exergy (amount of energy available to do work) in the form of chemical and/or gravitational potential energy, waste that is released to the environment does not drive a production process or do meaningful work. In the emergy accounting methodology, emergy allocation to waste flows is not standardized. Environmental accounting that allocates emergy to waste products may not conform to traditional emergy principles [37], and future developments in emergy theory may be required on this topic.

10.6 Conclusions and Future Directions

Our present-day society is focused on humans as consumers of things produced by the economy, as illustrated in the model shown in Fig. 10.11. People buy things that they need and want, and these things constitute our material culture. Some economists believe this consumption drives overall economic growth and that it should be encouraged. This model has some similarities with the P-R model shown in Fig. 10.1 in the coupling of production and consumption; however, unlike the balanced P-R model, waste flows are also emphasized in Fig. 10.11, as by-products of production processes and as disposal of things after they wear out or become obsolete. To some extent, these wastes are directly or indirectly a consequence of our "throwaway society" in which it is cheaper to dispose wastes rather than to recycle them. All of the waste flows in Fig. 10.11 are modern society's version of Tyler Volk's "wasteworld" model of the early biosphere discussed earlier. A direction for

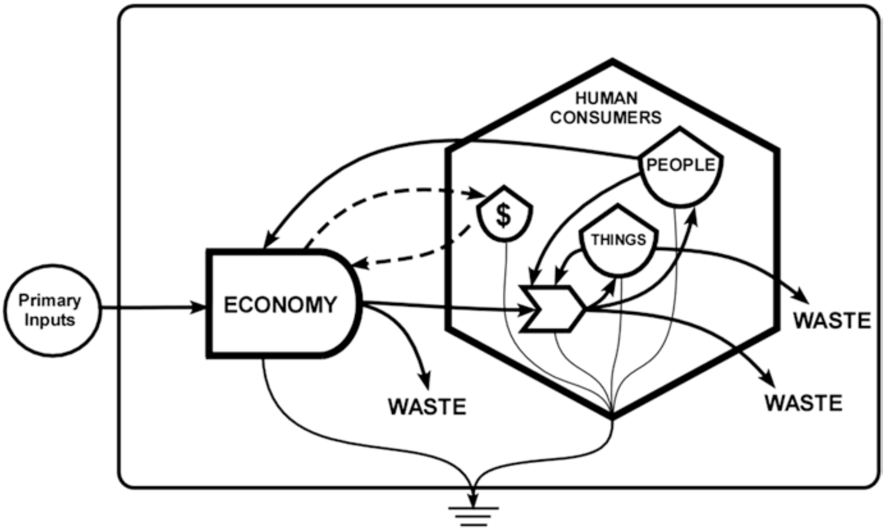

Fig. 10.11 Present-day economic system of consumerism and associated wastes

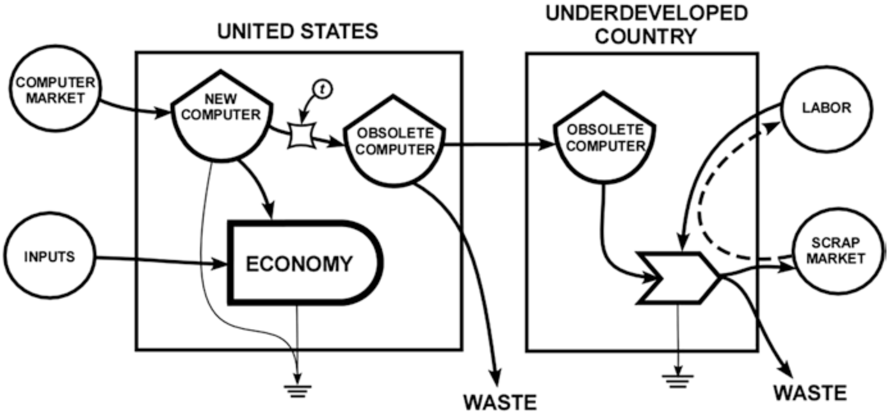

Fig. 10.12 Energy circuit diagram of the globalization of waste computer recycling

the future is to recognize and realize the values in the wastes so that systems will evolve to utilize the energy in the wastes and recycle the materials, just as in Gaian Theory.

When will economic selection favor recycling? There is no clear answer at present, but natural experiments in recycling are emerging all around us. One example of emerging recycling is shown in Fig. 10.12 with the recycling of materials in obsolete computers generated in the United States. New computers are used in the economy, but when they wear out or become outmoded, they become waste that we typically dispose of. This is the situation of "High Tech Trash," which leads to environmental impacts and losses of valuable materials used to make the computers (such as gold and copper) [38]. An interesting recycle loop has emerged with the obsolete computers being shipped to underdeveloped countries where labor is cheap enough to recycle materials that otherwise would be lost. In this case, there is no value in the waste computers in the United States, but when collected and shipped to the underdeveloped countries, there is value in them that can generate a profitable business with money flow.

Another emerging economic circuit of material flow is that of thieves who steal copper wiring from existing communications and housing systems (Fig. 10.13). This copper is then sold in a scrap market to generate a flow of money to the thieves. This emerging economic loop is actually a kind of short circuit of the normal material cycle of copper in the overall economy. Apparently, to thieves, the risk of being caught stealing copper is outweighed by the value that can be realized in the sale to the scrap market.

The emerging economic circuits shown in this chapter illustrate the trial-and-error self-organization that is taking place in present-day society in regard to material cycling. Through industrial ecology and other pathways, we need to

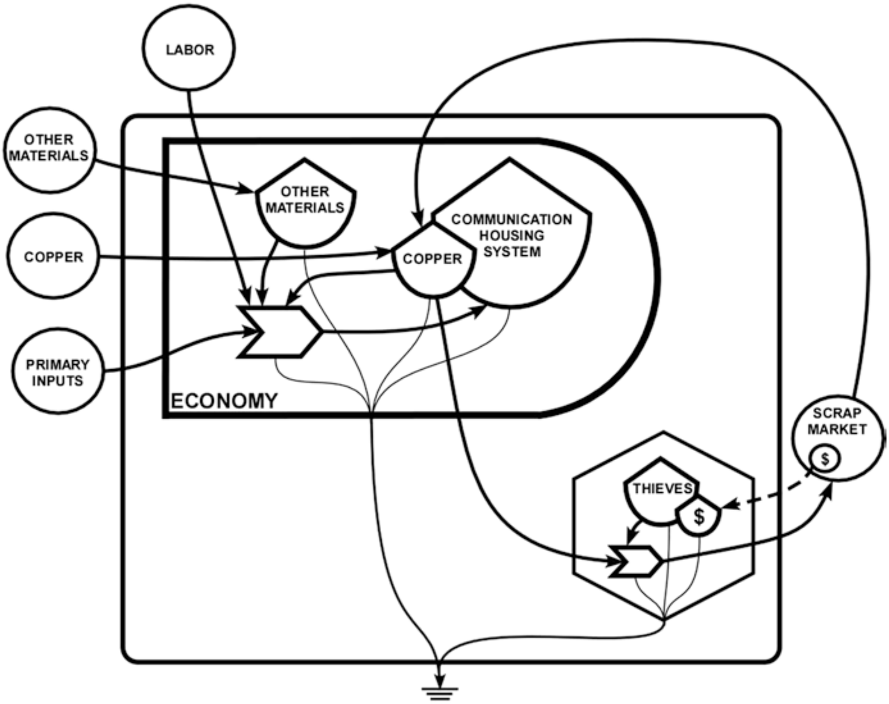

Fig. 10.13 Diagram of the short circuit of theft of copper material and sale to scrap market

evolve away from the throwaway society wasteworld to a more balanced, sustainable system of production and consumption, like that of naturally functioning ecosystems.

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Chapter 11
The Biological System: Plants in the Urban Environment

Myrna H. P. Hall

Abstract This chapter reviews the importance of plants to the urban environment. It summarizes the conditions to which plants are subjected in the urban environment and some of the benefits they provide both physically through cleaning air and water and psychologically. It reviews briefly the history of urban flora studies and the most common spatial sampling designs used by researchers to document urban plant species over time. While the majority of past research has focused on taxonomic cataloging of the species found in cities, with a particular emphasis on native versus non-native, current urban plant ecology research questions revolve around the novel ecosystems being created in urban areas, evolution and physiological adaptation, and the role of human attitudes. Finally, we offer an energetics-based approach to understand species presence and absence as a function of their metabolic adaptation to multiple environmental gradients encountered across a heterogeneous urban landscape. Such knowledge, we propose, can help city planners, landscape architects, and citizens preserve urban ecosystem biotic structure and function in a changing world.

Keywords Urban flora · Rural to urban gradients · Environmental gradients · Natural analog · Optimum ecological space · Novel ecosystems

11.1 The Divorce of Nature and Culture

With the advent of cities, urban dwellers became increasingly disconnected from the life-supporting natural systems that provided their sustenance. Environmental historian J. Donald Hughes describes how this separation between the agrarian life

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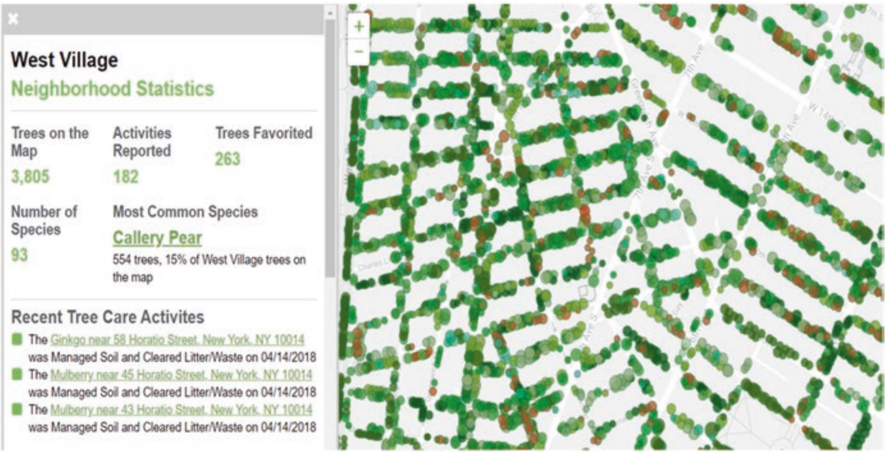
outside the city walls and the urban life within caused people to become less aware of the early warning signs of environmental degradation that would have been acutely obvious to earlier Paleolithic hunter-gatherer societies [1]. As resources became depleted, this “divorce” of nature and culture, contributed to a decline in the socioeconomic activities or metabolism of people’s daily lives, and eventually to the collapse of many ancient cities. Interestingly the discipline of ecology over its history has perpetrated this separation by focusing on wildlife and wild systems rather than those in which human management and human intervention play a primary role. Today the US National Science Foundation supports coupled nature-human systems research, and the new emphases in ecology and ecological economics on ecosystem services, ecosystem sustainability, and ecosystem resilience are attempts to reconnect people’s understanding and appreciation for the importance of nature to human society, even to the point of assigning a monetary value to the services of nature [2].

Despite this theory of the separation of urban dwellers from the “wild,” there do exist many places in cities where people experience a connection to the qualities of what we will call the *non-urban environment*, rather than *nature*. This connection is experienced primarily through the vegetated areas of the city—parks, community gardens, treelined streets, residential yards, remnant forests, and urban waterways—and through the wildlife species that inhabit those spaces. As a species people tend to be biophilic, meaning we love or at least have a great affinity for both plants and animals (Fig. 11.1). A city without parks, trees, flowers, and animals is a foreign environment to the human spirit. Researchers have discovered that urban green spaces enhance both physical and mental human health through, for example, crime reduction and community-building [3] or faster postoperative healing [4, 5]. Children have been shown to benefit psychologically from early contact with nature [6]. Not only do flora and fauna provide psychological services, but also urban trees and other vegetation provide many ecosystem services as we have seen in earlier chapters. They help modulate surface runoff, reduce both surface and ambient air temperatures, remove air pollutant particles, and so forth, all making our cities more habitable. In addition, they provide habitat and nourishment for mammals, macroinvertebrates, herps, insects, and birds and help build soil. These ecosystem services are critical to the survival of all organisms. The City of New York is so cognizant of the importance of vegetation to the socio-ecological metabolism of the city that it has now mapped every tree (Fig. 11.2).

11.1.1 Why a Study of Urban Flora Is Important

There are several important reasons to study plants in the urban landscape that are presented here and perhaps you can think of more. The first is that knowledge and information make it easier for us to overcome obstacles and to find solutions to the

Fig. 11.1 Biophilic urban ecology students, SUNY College of Environmental Science and Forestry, Syracuse, NY, (**a**) feeding the Webster Pond ducks; (**b**) learning about benthic organisms in an urban stream's headwaters; (**c**) seining for fish in Onondaga Lake, Syracuse, NY (Source of images: Myrna Hall)



West Village

Neighborhood Statistics

Trees on the Map	Activities Reported	Trees Favorited
3,805	182	263

Number of Species	Most Common Species
93	Callery Pear 554 trees, 15% of West Village trees on the map

Recent Tree Care Activites

- The Ginkgo near 58 Horatio Street, New York, NY 10014 was Managed Soil and Cleared Litter/Waste on 04/14/2018
- The Mulberry near 45 Horatio Street, New York, NY 10014 was Managed Soil and Cleared Litter/Waste on 04/14/2018
- The Mulberry near 43 Horatio Street, New York, NY 10014 was Managed Soil and Cleared Litter/Waste on 04/14/2018

Fig. 11.2 Map of West Village New York City trees and maintenance record (Source: https://tree-map.nycgovparks.org/#neighborhood-98) (With permission of NYC Department of Parks and Recreation)

urban environmental issues we face. Since over half the world's population now lives in cities, and the World Health Organization projects that proportion to reach 70% by 2050, that means more cities will be built, and fewer and fewer of the world's children (and adults) will have immediate access to nature. At the same time, climate change, additional human alteration of the landscape, and increasing fuel costs may make it more and more difficult to maintain urban green spaces as plantings will be physically stressed and/or cities will not be able to afford the cost of maintenance. To understand how to maintain urban flora for its positive effects and how to do that in a way that will be resilient to these almost certain futures, we need to study the biophysical and social factors that contribute to the survival (or lack thereof) of plant species in the urban environment. The first questions we might ask are (1) what plant species thrive in cities and why; (2) what plant species are most likely to thrive in the future; (3) what controls their geographic distribution; and (4) how do they adapt to the human-altered environment? Armed with this knowledge, perhaps we can figure out how to work with nature and people to create sustainable, resilient urban plantings that can reduce the energy and monetary costs of frequent maintenance and replacement. This requires knowledge of current distributions of urban plants along gradients of soil substrate qualities, moisture, air temperature, available sunlight, etc., as well as the pathways of plant introduction to the city and the ecological processes of building functional urban habitats. The role humans play in orchestrating all of this, whether directly, through their cultural, social, or economic preferences, or indirectly through their daily movement patterns, purchases, or waste, etc., must also be considered. If trees, flowers, parks, and gardens are to endure, and endure with the least need for expensive maintenance, then city planners, horticulturalists, and landscape architects need to be able to answer the four questions posed above.

In addition to the challenge of providing green urban habitats in the face of an ever more urbanized and environmentally-altered world, there is a second good reason to study urban plant ecology. Many ecologists see cities as immensely interesting places to study both plant and animal life, not only because of the emerging novel ecosystems that form under urban environmental conditions, but also because there are so many interesting questions to pursue, such as (1) whether the same assemblages of species occur across multiple cities, i.e., the process of homogenization; (2) why this phenomenon may or may not be true (species may be the same but measures of abundance and dominance, for instance, may show considerable heterogeneity across cities); (3) what physiological, behavioral, and genetic adaptations species undergo in the face of urban environmental alterations away from the conditions in which they evolved; and (4) what social, economic, or ecological factors explain the presence, absence, isolation, or success of species in cities. Such research provides insights not only into the evolution and ecology of plants and animals in general but also provides some interesting "clues" to the social and economic history of a city and the region in which it is located.

11.1.2 Habitat Conditions Unique to Cities

Urbanization transforms nature. As people try to create liveable habitats, they often remove topographic irregularities. They channelize streams or, worse, bury them underground. They drain wetlands, uproot trees, scrape away topsoil, and pave what remains with cobbles, bricks, concrete, and asphalt. Even where vegetation is present, the activities of lawn mowing and heavy pruning of trees and shrubs alter the natural succession of plants required to create a fully nutrient-retentive ecosystem. Ecologically we can say that lawn maintenance keeps sites in an *arrested* successional state. Urbanization creates conditions that stress the metabolism of some species. Built structures block or intensify sunlight at ground level or funnel winds that affect plant transpiration; pavement reduces planting areas and alters soil and air moisture regimes. Together the materials from which both buildings and paving are constructed store and slowly emit heat that may make urban areas more habitable for some species that evolved in similar natural environments, or less habitable for those that experience too much heat-induced evapotranspirative stress. The alteration and compaction of soils during construction reduces the availability of air and water to plant roots. In fact, urban soils are altered in so many ways, often multiple times through their history, that they do not display the typical soil development of undisturbed sites where one finds well-defined soil horizons that are favorable to root development and adequate air and moisture (Fig. 11.3). Rather they are a mixture of different horizons (e.g., substrate with topsoil) and construction materials. They tend to be alkaline due to the concentration of high pH building materials (bricks, concrete, and mortar) both in the soil and surrounding planting areas. Chemically they are often higher in salts, especially in northern climates due to winter salt application to melt ice on city streets and sidewalks. Some studies

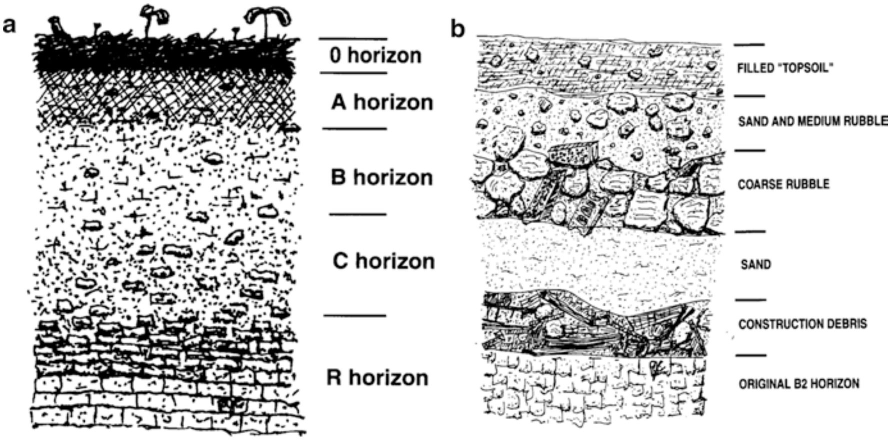


Fig. 11.3 (**a**) A natural forest soil; (**b**) an example of an urban soil (Source: [59] drawings by Dr. Phil Craul, with permission of authors)

have found higher nitrogen levels in soils of the urban core than in rural ones [7–9]. In such an environment of ongoing disturbance, it is often difficult or costly to establish and maintain plants.

11.2 The Sources of Plant Species Found in Cities

There are both biophysical and social factors that explain what species of plants are found in a city. These include the species of plants that naturally occupy the region where a city is established, the strategies of plant species developed through natural selection to survive under different environmental conditions, and the introduction by humans both intentionally and unintentionally. To these we should add dispersal mechanisms of both native and non-native plant species.

11.2.1 Ecoregion Influence

Observation of vegetation, in an urban area, where humans have not actively planted anything, reveals at the macroscale that the plants found originally in the region where a city is established will have a greater likelihood of being found within that city. This is due to the regional environmental conditions and the locally available seed pool, which is determined by the climate and soils of the region. This should be obvious. In nature we do not find the same plants in desert environments that we encounter in alpine meadows or tropical humid forests. Hence it is unlikely that you will find natural establishment of palm trees in Minneapolis, Minnesota, or Bergen, Norway. Cities like Seattle and Yokohama have species from evergreen forests, and this can be explained by the locally available seed pool (a storage). In the Eastern deciduous biome, one finds remnant forest patches in cities with species similar to those in the surrounding area as well as patches of marsh, grassland, and agroecosystem. Of course, many of these patches will not mimic perfectly, nor retain the species of, the surrounding area due to radical changes in the hydrology, sunlight, soils, and nutrients, in the urban environment. Furthermore, species composition frequently includes many non-natives introduced by humans either deliberately or accidentally. In the urban garden these species may be more lush or we may find more water-demanding species because of irrigation. The main difference, however, compared to the rural environment is that generally in the city, the vegetation occurs in much smaller patches, from large parks down to backyard gardens and vacant lots to sidewalk cracks. In addition, human management frequently changes what was originally a forest-type environment, particularly in parks, into a savanna-type environment with the trees more widely separated and with managed herbaceous (lawn) patches or macadam in between. Studies by Nowak and others document the influence of local ecoregions on forest cover in cities across the United States [10, 11]. They found that urban tree cover is highest in forested ecoregions (34.4% on average), but only 17.8% in cities located in grassland regions and 9.3% in desert regions. The species of trees and other plants found in these locations have adapted to the conditions of these regions not only due to climatic controls or soil characteristics but also due to centuries of disturbance in the form of grazing, fire, floods, avalanches, etc. Over time that locally-available seed storage may be diminished as the urban area expands farther and farther into rural areas. Hence, what is called the "seed rain" (a flux) may become more important than the storage pool. If we consider a recently disturbed and denuded urban site, there may be no immediate native species seed pool. To become vegetated the site depends more on the seed rain, or influx of seeds from within and without the city via the wind, the rain, birds, animal transport, etc. So ecoregion determines the initial seed pool, but humans can change this percentage, of forest cover for example, through management action such as tree removal for utility rights of way or crime prevention, selection of other species, increased irrigation, etc. (see section on Human Influence).

11.2.2 Evolutionary Strategies of Plants

The evolutionary strategies of plants through natural selection predispose them to establishment and survival in urban habitats. Ecologists often speak of the natural analog for plant species. For example, plants found growing in sidewalk cracks (e.g., *Plantago major*) are often the same as those found in excessively treaded permanent pasture, the natural analog environment (Fig. 11.4). *Natural* here does not necessarily mean prior to human activity. Humans have grazed domestic animals for centuries. Rather, as explained earlier, it is intended to mean non-urban. Müller and others have shown for six cities around the world that most urban species identified

Fig. 11.4 Broadleaf plantain, *Plantago major*, thriving in an urban sidewalk (Source: Paul Braun, https://www.inaturalist.org/photos/19737733, CC_BY_4.0, https://creativecommons.org/licenses/by/4.0/)

derived from grasslands and riparian areas [12]. All of the cities inventoried are situated at river mouths, on rivers, or at the outlet of large riverine systems, thus explaining the seed pool for riparian species. However, the high proportion of riparian species and grassland species may be due to their evolutionary strategies that predispose them to survival in highly disturbed environments due to floods in the case of the former, and in the latter, to fire and grazing. These highly stressed environments are not unlike the urban environment. Grassland species may be preadapted to the low-moisture habitats of urban areas and riparian species to extreme oscillation in soil moisture. These plants are more likely to continue to evolve as growing conditions change by changing behavior, structure, and physiology. They may hybridize naturally, keep stomata closed for longer periods of time, put out a huge number of seeds when stressed, grow deeper roots than in the wild, etc. This is part of the evolutionary process.

11.2.3 Influence of Humans

Although the biophysical attributes of cities and their environs and the evolutionary traits of plants and their energy requirements explain a great deal about the abundance and distribution of plant species in the unique habitats of the urban environment, the most important causal agent explaining their presence (or absence) in a city is people, whether through indirect happenstance or direct choices. Indirect influence is seen in the habitats people have created simply by urbanizing and living. Through the importation of grains and other commodities, the seeds of many *weed* species have been introduced. They are escapees from transported grains either as part of a seed mix or as a weed seed mixed into the bags of grain. They have been documented especially along highway and railway corridors, at railway depots, industrial sites, shipyards, abandoned sites, brownfields, or even community gardens where they become naturalized without intentional planting by man. The

Fig. 11.5 Example of an urban savannah, English landscape design, London, UK (Source: Myrna Hall)

pace at which this is happening appears to have been accelerated due to globalization. They may arrive at these disturbed sites as seeds carried either by the wind or water or in the fur or excrement of passing mammals or birds although urban ecologists have identified the primary route of entrance is usually due to human activity.

Direct influence includes the intentional choices made by city residents, planners, and landscape designers as to what to plant and in what configurations. Gilbert observed that generally the human-determined vegetated landscape of cities consists of three primary forms – the *gardenesque*, the *technical*, and the *ecological* (Fig. 11.5) [13]. To this we should add a fourth, the English. The gardenesque takes on different forms in different cultures, for example, more formal in France and Italy than in England, and it is generally the most favored.

The English landscape is characterized by broad expanses of lawns punctuated by trees. Dubos speculated that humans feel most at home in this type of landscape due to its similarity to the open savannahs of Africa in which we evolved (Fig. 11.5) [14]. This style has been found to be ubiquitous across all the countries of the English hegemony—Australia, New Zealand, Canada, and the United States—or wherever the English have settled including parts of Argentina, South Africa, and India. Some studies indicate that not only the landscape style but the species found in these countries are quite similar [15]. This may explain the American obsession with the perfect lawn [16]. Usually this landscaping approach is the most expensive and energy intensive due to irrigation, the use of lawn mowers, fertilizers, and herbicides.

Fig. 11.6 Examples of three kinds of urban vegetated landscapes: (**a**) technical, (**b**) ecological, (**c**) gardenesque (Source: Myrna Hall)

The technological landscape consists of such things as linear highway planting strips, concrete planting boxes placed around urban squares or at the entry of urban buildings. These add some softness to the built environment but do not give one a sense of nature in the city. The third form, called the ecological, is applied to the vegetated landscape that has resulted without any human investment. Some are remnant landscapes not overtly meddled with by humans. Others consist of vacant housing lots and abandoned former industrial sites, brownfields, waste heaps, unfinished construction sites, etc., where species have become established through colonization and succession (as described above) over time. It is sometimes referred to as *spontaneous* or *messy* landscaping. These sites offer the richest opportunity to study what species occur "naturally," even with the disturbance factor, whereas the gardenesque landscape reveals more about human influence on urban species diversity. The ecological landscape can also refer to plantings initiated by humans to mimic the processes of succession found in, for example, a natural woodland, pond, or prairie field. These areas tend to attract more wildlife than does perhaps the gardenesque or technological landscape and obviously are cheaper and less energy intensive to maintain. This type of landscape design has been implemented in the Netherlands perhaps more than anywhere else, to give urban residents a higher sense of contact with nature. Most cities around the world contain a mixture of all three.

Other studies have shown the influence of household economics on the heterogeneity of plant species composition found in gardens across a city [17]. The influence of the global nursery industry probably explains the high level of urban plant diversity within a city and similarity across multiple cities because of the types of plants the industry offers for sale [18, 19]. Most of the cities studied have been in the temperate world. Although the taxa (species) documented in these studies may show these cities to be *taxonomically* similar, we might discover that, in fact, they still are quite different *ecologically* if abundance of each species, dominant species, etc. were quantified.

11.2.4 Dispersal Mechanisms

We cannot leave a discussion of the sources of urban plant species without briefly mentioning how seeds are dispersed. This was referred to earlier as the seed rain. Birds, mammals, and humans all play a role. Seeds are designed to fly with the wind or attach to animals or clothing. Some require passing through an organism's intestinal tract. Not only do they arrive in the "seed rain" or via rivers from upstream regions but also in boxcars of grain, garden seed packets, nursery plant pots, food products, and in our suitcases. They are attached to our sporting equipment, wading boots, recreational vehicles and tire treads. That is why when you travel internationally, you will be questioned upon return by customs officers who, in an effort to prevent invasions of non-native species and/or plant diseases, will inquire whether you have seeds, fruit, or flowers in your possession or whether you have visited a farm.

11.3 A History of Urban Plant Studies to Date

The study of urban flora is not new. As early as 1643, Panarolis catalogued the plants found on the Coliseum in Rome [20]. The species found in the rubble and walls of castles and ruins were of interest to many of those first studying urban plant communities because they mimic the substrate (soil or rooting materials in particular) and microclimate conditions found in cities. *Ruderata* (from Lat. rudus: rubble, rubbish, ruins) is the name for habitats where human activity has left rubble and rubbish heaps. Hence the species that first occupy these sites are called ruderals, and the word has become synonymous for early successional species, i.e., the first to establish post disturbance in an urban environment. Castles and old walls, even those not *in* cities, provided good places to observe plant responses to establishment of the built environment. These sites are generally rich deposits of human waste materials that provide nutrients to plant species, which took advantage of this metabolic boost. Observation of plants found at these sites also helps us document human history, particularly the kinds of agriculture that occurred near them. This gives us insight into the historic regional sources of plant species found in a city of that region today.

In 1823 Schow introduced the term *Plantae urbanae* for plants living *near* cities and villages [21]. In his view it was human settlement that explained the presence of what he called species of “foreign origin,” i.e., non-native species. Around the same time in 1827, Chamisso described the conditions and effect of humans on the flora and fauna of settlements as follows:

> Wherever man settles, the face of nature is changed. His domesticated animals and plants follow him; the woods become sparse; and animals shy away; his plants and seeds spread themselves around his habitation; rats, mice and insects move in under his roof; many kinds of swallow, finch, lark and partridge seek his care and enjoy, as guests, the fruits of his labor. In his gardens and fields, a number of plants grow as weeds among the crops he has planted. They mix freely with the crops and share their fate. And where he no longer claims the entire area his tenants estrange themselves from him and even the wild, where he has not set foot, changes its form [22].

Though much more recently, in 2011 Celka surveyed 109 fortified settlements and castles in Central and Eastern Europe and concluded that these sites were concentrators of species, quite distinct from the surrounding natural environment, and were subsequently sources of dispersal of non-native species that became the weed species that plagued farmers of the region for centuries to come [23].

Most of the studies that followed the earliest ones attempted to differentiate between the wild (native) and alien (non-native) species, to document those that became naturalized, and identify the new species created in urban areas. Native species are defined as those that survived or recolonized in the same region after the last ice age. Researchers categorized non-natives into two types. The first, called archaeophytes, had been introduced by agriculture and animal husbandry before 1500 CE, in Central Europe, for example, and the second, called neophytes, were those arriving after 1500. This pivotal year also corresponds roughly to the beginning of transoceanic navigation and the introduction of species to Europe from the Americas and Asia. A third category that is commonly found in cities are anecophytes, species that are such generalists that there is no identifiable natural habitat. They have evolved through hybridization or natural selection only in anthropogenic environments. Some examples of these are shepherd's purse (*Capsella bursa-pastoris*), lamb's-quarters (*Chenopodium album*), Bermuda grass, mouse barley (*Hordeum murinum*), common plantain, annual bluegrass, prostrate knotweed (*Polygonum aviculare*), common groundsel (*Senecio vulgaris*), common chickweed (*Stellaria media*), and common dandelion. These are some of the most common species in cities around the world [24].

The first urban ecology studies that looked at the relation of species to the ecological conditions of urban habitats came after World War II in Europe. The ravages of the war left immense areas of bare soil or rubble upon which plant species became established without direct human action, i.e., seeding/planting. This situation provided a rich template upon which to document the natural changes or natural succession of vegetation species that occurred over time in a very urbanized setting. European ecologists saw the great opportunity provided by these disturbed urban sites to study immigration of species to these sites and the development of urban plant community structure and function over time. Studies of, for example, Vyborg (Russia), Rotterdam, London, and Berlin indicated that species from warmer regions of the world had taken hold in these rubble environments of cold northern cities. Later studies have supported these findings by showing that southern species, the farther north one goes, are found primarily in the urban core, or warmest part of the cities investigated. This is consistent with the concept that urban areas are warmer than their surroundings [25] (see Chap. 7).

11.4 Different Sampling Designs Employed to Understand Variation in Plant Species Across a City

How have ecologists attempted to understand the effect of urbanization on the distribution of plant species? Usually they have employed one of five data gathering designs or sampling schemes, either (1) along a transect from less densely developed to more densely developed urban areas, which is often called a rural to urban gradient, (2) in different urban biotopes (highly specialized human-designed use areas), (3) across a matrix of different land cover patches, (4) between different socioeconomic neighborhoods, or (5) applying a grid to a geographic area and selecting random sampling points.

11.4.1 Urban Species Presence/Absence and Distribution as a Function of Urbanization Density Along a Rural to Urban Gradient

In the first approach, called a gradient analysis, researchers inventory plant species from the densely paved and densely populated urban core radiating out through less dense residential areas to ultimately the urban fringe, i.e., where the city meets the surrounding countryside. Since many cities do not follow this idealized form of concentric urbanization densities, researchers would select sites that varied in terms of the degree of human alteration to the formerly non-urban landscape. That metric was based primarily on the density of built structures that would theoretically represent an urbanization gradient of less to more alteration or human disturbance. Across this gradient it is *assumed*, but not usually *measured* simultaneously, that the abiotic environment changes in terms of temperature, moisture, soil conditions, and light availability from what is found in the more vegetated, less disturbed “natural” environment. It is expected that the least optimal conditions for plant success would be found in the urban core or most densely built-up area and that taxa abundance and richness would increase with distance from this most highly altered environment. The gradient approach, by sampling from less modified to more modified sites, is also a means of replacing space for time, with the assumption that over time, the species present have displaced the native species that were once found in the *pristine* forests or grasslands that historically occupied the area. This would occur progressively as urban conditions spread outward from the core.

11.4.2 Urban Species Presence/Absence and Distribution as a Function of Biotope Characteristics

A second spatial organization for looking at distribution and abundance of urban species is organized around the concept of biotopes or different human-created plant habitats. The term biotope, as originated by the German ecologist Haeckel, signifies the habitat prerequisite to an organism’s existence and is thus very much related to evolutionary adaptation. The word taken apart means the place (topo) where biological (bio) organisms live. But when applied to studies of urban plants, the habitat is no longer that found in non-urban but rather places in the city with uniform soil and climate conditions and identifiable boundaries, characterized by a particular element of the built environment created by humans. Biotopes, therefore, can include cemeteries, parks, walls, sidewalks, railway corridors, industrial sites, private front yards and backyards, ponds, etc. Given the influence of humans in creating these biotopes, this is an interesting social-ecological approach, whereas the urban density gradient tends to be more biophysical. The biotope approach was derived in part from Ramenski’s 1928 early work on the ecological distribution of species, which was also concerned with the communities of species that coexist and how they changed as a function of changing environmental conditions [26, 27].

11.4.3 Urban Species Presence/Absence and Distribution as a Function of Land Cover Configuration

The third type of spatial organization of sampling is derived from landscape ecology and attempts to catalogue species over patches of different land use/land cover types. These land cover types are often those identified from aerial photography or remote sensing and can include open areas of grass (such as playgrounds, ball fields, and parks), remnant forests, commercial districts, industrial areas, and different densities of residential areas, each with varying amounts of hardscape versus vegetation. While this classification of spatial areas in a city may not seem different from the former, it is very much focused on the pattern of these land cover patches, and their isolation or connectivity, with less emphasis on human uses. This method derives from the field of landscape ecology where it has been used extensively to understand wildlife distribution, patterns of disbursement, and home range. It is premised on the notion that spatial pattern is the primary driver in affecting how species are distributed initially and how they move (or not) across that landscape. This approach has been particularly prevalent in the United States. The city is viewed as a heterogeneous landscape or mosaic of individual patches each of homogenous land cover. Adjacency of neighboring patches plays a key role in explaining the pattern of plant distribution across the city, as does the degree of patch density, an indication of how disconnected and dissimilar one area is from another, presumably thus affecting species response and ability to survive. Where habitat patches of like kind are connected, corridors are created that allow migration of species, both plant and animal, native and non-native, across the cityscape. Larger remnant patches usually contain a greater number of native species [28]. Where patches are very isolated, a species that may be entirely lost somewhere else is preserved in say a remnant forest within the city. This is a concept borrowed from island biogeography.

11.4.4 Urban Species Presence/Absence and Distribution as a Function of Neighborhood

The neighborhood approach is a fourth type of spatial organization used for vegetation sampling across a city. This approach considers variation in social, cultural, economic, and demographic characteristics that influence the choice of plant species, their distribution and abundance, and investment in care and maintenance. Studies of such direct human influence on urban vegetation date to the mid-1980s when urban forester Richards and others and landscape architect Palmer evaluated the variation in urban tree and shrub species, their abundance and maintenance across neighborhoods in Syracuse, NY, to understand human attitudes, behaviors, and values toward urban vegetation [29, 30]. The assessment of flora was inferred through observation of neighborhood planting characteristics, while the assessment of human values employed direct survey of household members to determine their perceptions and motivations with respect to plants in their yard and street green space.

More recent studies of the presence, abundance, and distribution of urban plant species separate public areas, controlled by a city agency (top down), from private areas, where planting choices are made by individuals (bottom up). It is not always easy, however, to get access to private areas, which often make up the majority area of a town's planted area; thus many studies have had to rely on public areas alone when inventorying urban species.

11.4.5 Urban Species Presence/Absence: Quantification Applying Random Sampling and Statistical Analysis

This has been a common approach to quantifying and tracking species abundance and dominance in both rural and urban locations. It is based on the use of statistical analytical procedures that allow us to draw conclusions about the population of plants as a whole from a smaller sample. Normally a grid is applied to the area of interest, and sample locations are randomly selected within each grid block using a roll of the dice or other random number generator to identify the coordinates within the grid where the identification and quantification of species present will be conducted. The purpose of the grid is to ensure sampling across the entire area of interest. The random selection of sample locations eliminates human bias, such as choosing a lusher site, a site closer to the road, a site with unique vegetation that one is curious about. If these same locations are sampled every 1, 5, 10, etc. years, the change in species composition, growth, health, and mortality can be documented and analyzed. This is the method used in the US Forest Service Forest Inventory Analysis (FIA) Program [31].

11.4.6 Urban Species Presence/Absence and Distribution Along a Successional Gradient

Another way to organize samples is that used by some urban flora scientists who are particularly interested in what species establish naturally in cities over time as a function of natural succession. Succession is the change in species composition on a site over time and often takes place because the environmental conditions in a location change over time. Each species that colonizes a particular location is adapted to thrive within only a certain range of environmental conditions (see Sect. 11.5). These conditions may change because the species themselves create new environmental conditions such as shading the soil, adding nutrients and organic matter, changing the light regime, etc. Due to these changes, the first species are replaced by other species which are better adapted to the new conditions. Sampling often is concentrated on once highly disturbed locations such as abandoned industrial and waste sites. Although succession plays an important role in the establishment of urban species, rarely does the full cycle of possible succession occur in urban landscapes (i.e., from what are called pioneer to mature species) given that disturbance is frequent. There are two types of succession, primary and secondary. The first is what you would find in the wild on say deglaciated terrain, where plants have not existed before. In the urban environment, similar conditions can be found on an abandoned parking lot, a sidewalk, an inorganic waste bed, or the rubble of a demolished building. The early colonizers or pioneer species of primary succession are typically lichens and mosses, which fix nitrogen and break down rocks so that sediment and water are trapped and other plants can become established. The mosses themselves hold water and provide a moist environment for seeds of other species to take hold. Secondary succession is that which occurs on previously vegetated sites or where soil is exposed, as when a tree falls in a forest and opens up the forest floor to sunlight, or a field that is tilled but not otherwise managed. In the city it could be an abandoned residential lot, park, remnant forest where a tree has fallen, or soil laid bare by construction projects. Here the pioneer species are more likely annual plants like dandelion, broadleaf plantain, and chickweed, for example, but may include high-volume seed-producing perennials like *Solidago canadensis* (goldenrod), *Achillea millefolium* (common yarrow), and *Daucus carota* (Queen Anne's lace). Note that these are species of the temperate North. Each region of the world will have its own pioneer species. We often call them "weeds." They take advantage of the abundant light (solar energy) and are tolerant of unshaded soils that heat up quickly and low-moisture conditions. They fill up a site aggressively through a huge energy investment into seed production, but often stems are not dense, and a canopy is created that is preferred by some wildlife, particularly some gameland birds that take advantage of the seeds and the cover. That canopy, however, will prevent their own seeds from germinating since they need abundant light; hence in 1 to perhaps 3 years, they will die out. The pioneer species lay down organic matter that helps build the soil for the species that follow. Once an organic soil with greater water holding capacity has had time to develop, the next round of slower colonizers that will last for a longer period arrive as the conditions have become what they need to thrive. They include flowering herbs and grasses, perennials, and woody plants that provide nourishment for herbivores that feed on them—birds, mice, voles, rabbits, and deer. With enhanced nutrient cycling, the environmental conditions change once again, making the site suitable for shrubs and trees. In a forest ecosystem, pioneer species can be trees like *Betula papyrifera* (*white birch*) and *Prunus serotina* (*black cherry*). Shade intolerant, they are followed by shade-tolerant seedlings that will eventually become the mature trees of a forested ecosystem. These will die when the conditions change again with a new disturbance, starting the cycle anew. Russian ecologist Ramenski, one of the first ecologists to study communities of species as a function of environmental gradients, distinguished among the functional successional traits of plant species by likening them to animals [32]. He likened the early opportunist occupiers to *jackals*, those that come next to *camels*, slower to colonize, stress-tolerant, and longer-lasting, and, finally, the mature species, to *lions*, due to their ability to completely dominate a site over time. Although not ecological classifications, nor entirely analogous, they provide a graphic description of the functional traits of plant species as they respond to changing environmental conditions of a site. The urban ecologist Grime classified them as R, S, and C species (ruderals, stress-tolerant, and competitors), respectively [33]. Each group has differences in what Grime called *strategies* that are really adaptations to particular environmental conditions resulting in differences in ecological *niche*, or the *function* that different types of species play in the ecology of a particular location or ecosystem. In that respect you might think of the ruderals or early opportunist pioneer species as the species that can colonize abiotic sites. In so doing they become site preparers that lay down the initial biomass and dead organic material that conditions the soil, followed by the stress-tolerant mid-successional species that tolerate low light under the canopy of other vegetation patiently waiting to take on the job of capturing energy and nutrients to the site once the other species die and finally the mature species that maintain full hydrological, nutrient, and energy functioning on a site creating stability for many species until the next round of disturbance. This progression can be observed on abandoned waste sites in many cities (Fig. 11.7).

11.4.6.1 Individual vs Community Responses

A long-standing question in ecology is whether plant species occur together as communities, where different species reinforce each other and hence co-occur (as in Clements [34]), or whether instead each species simply responds individualistically to environmental conditions (as put forth by Gleason [35]). Grime, as a plant community ecologist, appears to favor the former, which seems consistent with the frequent observation of plant species co-occurring together, and this perspective tends to dominate in much of the plant ecology literature. But if one realizes that each species of plant is responding to its own requirements along environmental gradients of sunlight, soil nutrients, temperature, etc., the co-occurrence of the same species together aligns with Gleason's theory that emphasizes individual species' response to environmental conditions of light, water, temperature, etc.[1] This is different from the community approach proposed by Grime in which communities of species occupy sites together and then gradually vanish as a cohort as the next step of succession occurs. Sukopp, in agreement with Gleason, i. e. in favor of the individualistic response, made this point very clearly for urban species complexes, saying, "Urban biocoenoses are an extreme example of communities produced by successive invasions and not by co-evolutionary development. In principle, the historic uniqueness of urban ecosystems, in other words their combination of environmental factors and organisms, differentiate them from most non-urban ones, even

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[1] This understanding of plant response along environmental gradients was first remarked upon by Theophrastus born circa 370 B.C.E., and then by Alexander Von Humboldt circa 1802, and furthered by the work of Robert Whittaker in the 1950s [61–63].

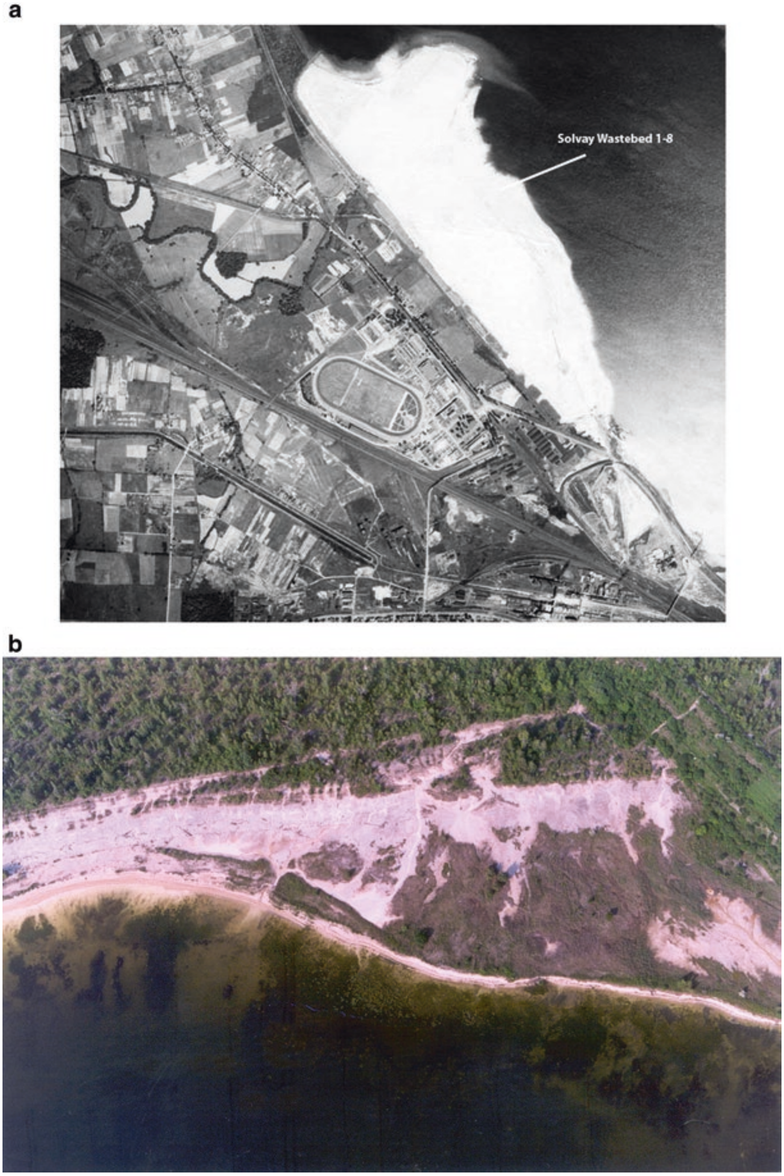

Fig. 11.7 (**a**) 1938 aerial view of chalk white Allied Chemical plant calcium chloride waste beds 1–8 along the shore of Onondaga Lake, Syracuse, NY. The waste was generated from the Solvay process production of soda ash. (**b**) 1990s aerial view of waste beds revegetating. (**c**) Successional vegetation on those waste beds today. Early successional trees (primarily *Populus deltoides* (eastern cottonwood)) in background are where dumping was stopped earlier than the area in the foreground where one finds grasses, sedges, and rushes both native and non-native. (**d**) Area still revegetating (Sources: (**a**) Photograph from Cornell University Library, New York State Aerial Photographs Collection Historical Aerial Photographs of New York (http://www.onondagalake.org/wp-revision/lake-history/)); (**b**–**d**) (Myrna Hall)

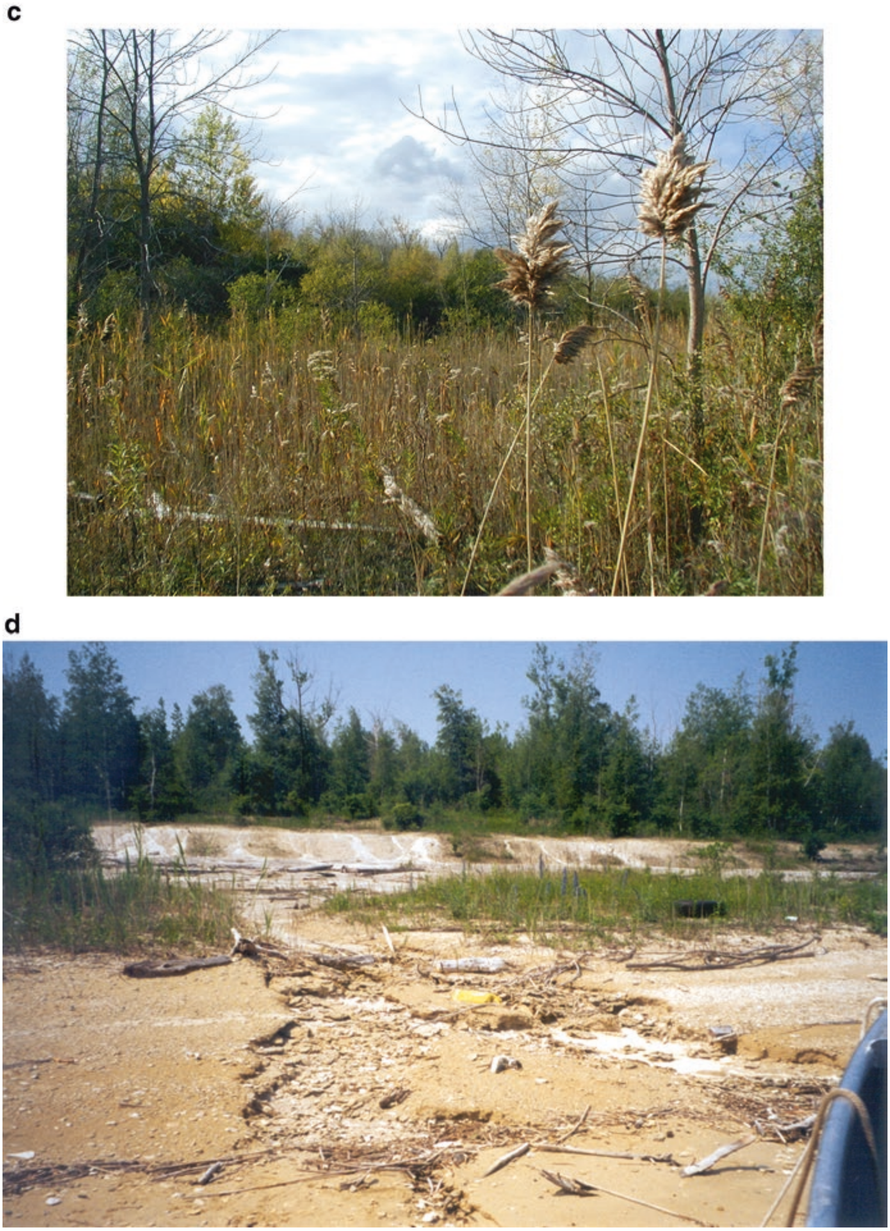

Fig. 7 (continued)

those subject to strong disturbance" [36, p. 312]. While this argument probably seems very esoteric to the beginning student, it is actually important to those trying to reestablish plant communities on highly disturbed sites. We believe that each species needs to be understood and managed with respect to its own life history and environmental tolerance and that is why we propose a different approach from the above in the next section.

11.5 Current Trends in Urban Flora Studies

11.5.1 Ecological Function, Species Evolution, and Changing Physiology

More recent studies of urban plants focus on ecological function and physiological mechanisms. There has been an emphasis on reconstructing native flora as *environmentally virtuous* [37]. However, with a growing emphasis on managing our cities for sustainability and resilience in the face of continuing human alterations of the landscape, climate change, and other environmental changes that affect soil, air, and water quality, such as earthquakes, hurricanes, and erosion, this emphasis on bringing back native species into highly disturbed environments may put too much burden on city budgets to guarantee their survival in an inhospitable environment [38].[2] Although there is some evidence that native plant species will support much greater animal species richness or Lepidoptera (butterfly) species richness, for example [39], non-native species complexes may be able take up the functions of native species, i.e. fill their niche ecologically while having superior survival abilities in disturbed environments. This is an ongoing research question. Some researchers are exploring evidence of cross-breeding of native and non-native species resulting in new hybrid species [40]. Do those hybrids fill the same ecological *niche* as those they replace (e.g., are native American bittersweet and non-native oriental bittersweet in the New York City region cross-breeding as they were shown capable of doing in the lab in 1947 [41]), filling the same niche as the native tree, or does the hybrid result in a more invasive species [42]? Others are looking at evolution of species as they adapt to survive in urban environmental conditions, although so far there has been more attention to insects and animals than to plants [43]. These are newly detected phenomena in urban areas, particularly with regard to animal and insect species. The term for these adaptations in the urban environment is HIREC, or human-induced rapid evolutionary change.

In addition to understanding the function of species in these new assemblages, or the controls on species diversity, newer research is also beginning to focus on what physiological mechanisms of the species themselves explain their presence, abun-

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[2] This is not to say that reestablishment of native species is not without benefits (see Tallamy and Shropshire [39]), only that if urban conditions do not favor those species, then it behooves us to plant those species that will thrive.

dance, and distribution. Some species have been found to “behave” differently in the urban versus rural environment, for example, shutting down stomata to preserve vascular turgidity under the greater evapotranspiration stress of the urban environment [44]. Taken together the objective of most of this research is to find ways to revegetate our urban environments with attractive and useful but tough plants in a pleasing and reasonably inexpensive way. There are many opportunities in this area for young people interested in growing and understanding plants that will help make our cities more enjoyable, psychologically calming, and sustainable.

11.5.2 Human Attitudes

There is increasing interest among urban ecologists in citizens’ attitudes and willingness to participate in new vegetation strategies to modulate urban temperatures, reduce storm runoff, provide locally grown produce, or beautify visually- and economically-blighted neighborhoods through urban greening [45, 46]. Melendez-Ackerman and others evaluated yard management decisions across a gradient of rural to urban neighborhoods in San Juan, Puerto Rico, to assess the potential for enhancing green infrastructure and the many ecosystem services it provides that can contribute to urban sustainability [47]. Like the Palmer study cited earlier, they also used both household surveys and observation. The authors emphasize the role of social-ecological factors occurring at the household scale.

11.6 An Alternative Energy-Based Environmental Gradient Approach

While studying plant diversity along an urbanization gradient, across biotopes, within a land use matrix, across a randomly selected set of points, and between different neighborhoods is informative, the results of these studies do not tell us much about the ecological requirements of plants to survive and grow, in other words, to make an energy profit or maximize their metabolism. In the former types of assessments, environmental conditions are aggregated into human-defined habitats for the most part. But don’t we need to know which species are well-adapted to urban growing conditions and which will thrive across the expected changing conditions of climate, water availability, energy constraints and shrinking urban budgets? We think so and, therefore, recommend an alternative approach that we call energy-based gradient analysis [48]. It is focused less on habitat or place and more on metabolism or the energy response of species along gradients of the biophysical factors that they need to germinate, grow, and reproduce. In nature, plant species have evolved through natural selection to take advantage of the specific light, moisture, nutrient, and disturbance conditions with which they are presented. From this perspective physiological adaptation to one location along an ecological gradient (say from wet to dry soil or to a different temperature) is done at the expense of adaptation to a different gradient condition. This has allowed them to adapt especially well to the specific conditions of their particular environment. Some species have wide tolerances while others are more sensitive to small changes. Maples tend to be on wetter soils, oaks on drier soils, and so on. Each gradient from low to high, less to more, represents habitat conditions such as cool to warm temperature, low to high soil moisture, and uninterrupted sunlight to intense shade. Charting species along an altitudinal gradient, which is really primarily a temperature gradient, was first proposed by Whittaker in 1967 [49]. The addition of the energy or metabolism perspective reveals that along a single gradient, where the growing conditions to which a species has adapted are optimal, a plant of that species can invest more of the energy it takes in from the sun toward its growth and reproduction. This is where the charted abundance curve peaks (Fig. 11.8). Over its range a species' abundance or growth is expected to take the form of a normal distribution or normal curve. At the outer limits of a species' range of tolerance, its abundance is low. At that point or under the ecological conditions represented by that point it may survive but not be able to make an energy profit to invest in production. This explains why a species may be extirpated when disturbance alters the moisture or temperature found in the geographic location where the species once thrived and another species better adapted to those conditions arrives on the scene. A species' optimal ecological location is where its favored combination of sunlight, moisture, and temperature conditions coincide. There it will also be able to outcompete other less *fit* (for that ecological location) species [48]. This ecological optimum can be visualized as the point at which multiple gradients coincide much like the space of each component of a nested Russian egg. In practice, to understand where that ecological optimum lies for any given species in geographic space requires sampling not across habitats but across multiple environmental gradients. Recording and charting plant response (production/growth) using, for example, abundance, biomass, or stem density along a gradient will reveal the range of a species' tolerance to variation in sunlight, soil moisture, day and night temperatures, etc. The knowledge gained should lead to more resilient urban planting much as has been done with xeric (tolerant of very low moisture) landscaping in the desert southwest of the United States, Dutch ecological landscaping, and in the examples that follow.

An example using knowledge of the ecological requirements of plants based on natural selection can be seen in the work of urban soil scientist Phil Craul [50]. Prior to building New York City's Battery Park, a site that sits on the southern tip of Manhattan on top of a landfill, Craul did a biophysical site assessment. He examined the soil texture, soil bulk density, and soil drainage capacity and used a weather station to assess the solar patterns, ambient air temperatures, wind direction, and wind velocity of the site. All of these contribute to the site's heat budget and hence evapotranspirative stress a plant would encounter at that site. He fed this information into a computer model he wrote to assess the evapotranspiration demand that proposed species would encounter. From this analysis he recommended tolerant species and designed an engineered soil with the proper physical and chemical properties to ensure their growth and survival.

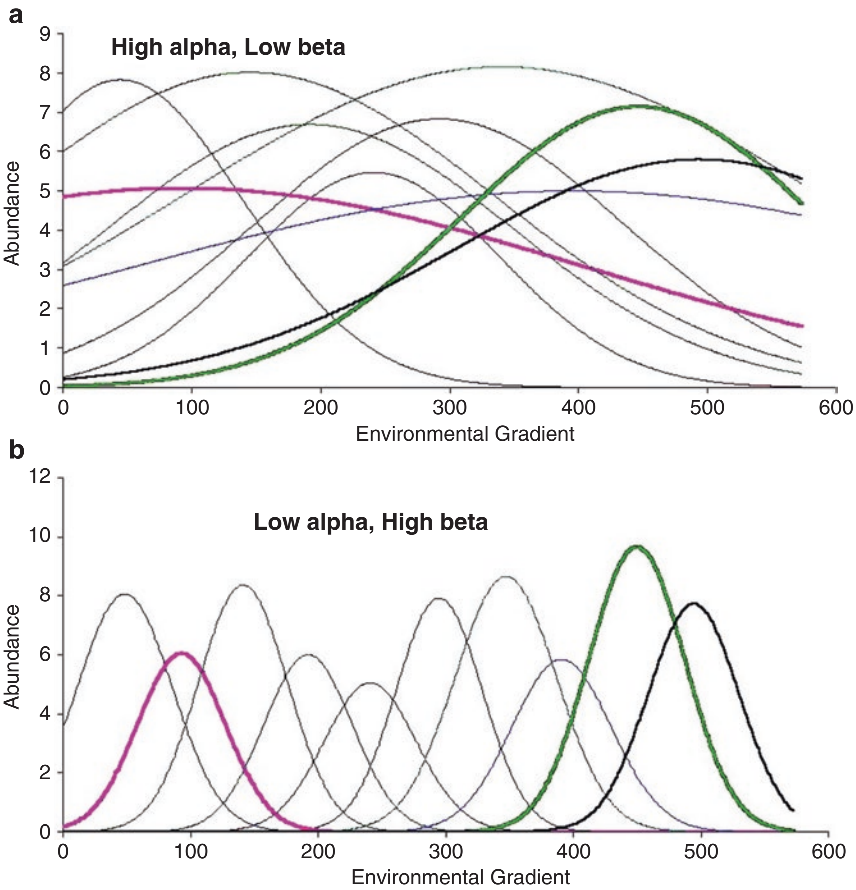

Fig. 11.8 Plant species abundance along a single environmental gradient. (**a**) Environmental gradient (e.g., temperature, sunlight, moisture) with high alpha diversity (high number of plant species at each location along the gradient), but not much change in species composition (beta diversity). (**b**) Environmental gradient with low alpha diversity (low number of species at each location along the gradient) but a high frequency of change in species composition (beta diversity). Used with the gracious permission of MW Palmer [60]

Another example that illustrates how a plant's energy-based evolution through natural selection helps it thrive in the urban environment is that of the ubiquitous urban tree *Ailanthus altissima* (see box inset).

Although *Ailanthus altissima* makes the highest energy profit, in terms of growth, in moist organic soils of high pH, it is drought resistant due to its ability to store water in its roots. It thrives in full sun such as offered by disturbed areas but has been found in low-light conditions such as dark shaded alleys, though growing more slowly. It evolved on limestone soils in Central China and is thus particularly suited to urban locations where the soil pH is high due to the presence of old brick mortar and concrete, although it also tolerates pH conditions as low as 4.4. Its ability to

Ailanthus altissima (Fig. 11.9) is a species that does best at the high end of gradients of both pH and sunlight but nevertheless exhibits tolerance to a wide range of environmental conditions. It is found in study after study of inner-city . It could be one of the species illustrated in Fig. 11.8a. It is originally from China and Taiwan. Also called the "tree of heaven," it was made famous by the best-selling novel *A Tree Grows in Brooklyn* 51.

Fig. 11.9 (**a**) *Ailanthus altissima*—several young trees (Source: Myrna Hall). (**b**) *Ailanthus altissima*—more mature tree growing under a concrete block (Source: Samuel Sage, Atlantic States Legal Foundation, Syracuse, NY)

withstand drought is also probably due to its evolution on calcareous (limestone) soils. These soils often have low water holding capacity due to their quick-draining structure. It is air pollution and ozone tolerant and takes up both sulfur dioxide and mercury. After World War II, it became naturalized in Europe due to the abundant rubble of destroyed buildings, upon which it thrives. In Berlin it occurs in 92% of densely occupied areas, 25% of suburbs, and only 3% of area outside the city [52]. This is only one of what Grime called urbanophile (urban loving) species, as opposed to urbanoneutral (no preference between rural and urban) and urbanophobic (fearing urban environments, i.e., not able to survive there) [33]. As appealing as these classifications are, they do not express the ecological relation of plants to the urban environment. It is not that plants love or fear an environment, but that they have evolved to make an energetic profit under particular growing conditions, some of which are found in cities, some of which are not. This approach could lead to a rethinking of how we structure new urban development or restructure existing, so that rather than making vegetated plantings an afterthought, they are considered first and the development designed to work around them. Soils, light availability, and temperature altering materials would be given priority consideration so that environmental conditions meet the favored ecological gradient space of species selected.

11.7 Conclusions

While comparisons of findings around the world are possible as more and more cities are inventoried, it remains difficult to draw generalizations across studies. As you attempt to answer some of the questions posed at the beginning of this chapter, remember that you need to consider the several issues that contribute to the difficulty of making comparisons. One is the difference in the spatial unit of sampling the researchers employed as described above. Another is the variety of sampling protocols employed. For instance, perhaps both private and public areas were investigated in some cities, but not others, or only naturally reestablishing areas were inventoried, but not those planted by humans. How land uses are defined, the scale of the sampling, or whether the sampling units (land uses or biotopes) are truly homogenous within the unit, all contribute to the difficulty in making comparisons. The unique morphology of individual cities, climatic differences, the definition of density, and the length of time over which changes were observed, all limit comparisons and generalizations. Some studies may have focused on documenting species as a function of time, while others focused on spatially varying factors. Nonetheless, nearly all inventories have recorded numbers of native versus non-native species and have drawn conclusions about taxa richness, taxa evenness, and overall taxa abundance (total number of plants) that allow for some generalizations. In addition, some concurrence on what controls urban plant species occurrence, abundance, and distribution has emerged.

The prevailing view is that the urban environment is a harsh place for both plants and animals to survive. These conditions have often led to the loss of native species. Research across 11 cities of North America, Asia, and Austalasia found that as much as between 1% and 35% of the species identified in initial floristic studies undertaken around the beginning of industrial development had disappeared within at least the last 100 years [53]. However, many other plants, perhaps not native to the region, can and do survive in urban habitats, especially where environmental conditions of light, temperature, disturbance frequency, or moisture availability mimic those in which they evolved. Despite the loss of native species, high biodiversity and new biotic communities called “novel” ecosystems are being reported [54, 55]. In 1979 German urban plant ecologist, Dr. Herbert Sukopp, stated, “Ecosystems which have developed in urban conditions may be the prevailing ecosystems in the future” [56, p. 32]. He suggested that by observing the new and well-adapted assemblages of species that establish themselves on disturbed urban sites, we can learn which native and naturalized non-native species will establish and thrive under changed environmental conditions. There is a growing view (see Lugo and others) that in the era of human domination of the world (the Anthropocene[3]) to maintain a balance between these newly emerging ecosystems and the rest of the world's biota will require management of biodiversity based not on preservation of native species alone but rather on understanding the function and dynamics of ecosystems [38, 55, 57, 58].

Understanding the evolutionary adaptations, metabolic requirements, and functional role of plants in an urban environment, as well as human affinity for urban vegetation, is important to deciding what species and combination of species to use in designing urban green infrastructure, whether in the form of (1) new parks and playgrounds; (2) stormwater management installations such as green roofs and bioswales, vegetated highway mediums, curb plantings, or rain gardens; (3) brownfield site remediation; (4) urban walking/biking paths; etc. The need for constant maintenance or for replanting of much urban vegetation and the costs incurred both monetarily and energetically are quite frequently due to lack of understanding of species' evolutionarily developed growing requirements and physiological strategies and their functional role with respect to other species in both establishment and longevity of an ecosystem. As we educate ourselves, we should in turn be better able to help the public understand and protect urban flora.

If we are to create cities where humans are not completely cut off from nature, where we allow plants to work for us through the services they provide, where songbirds and other urban fauna have food and habitat, where the cost of maintenance of urban biota does not strain city budgets, and where the impacts of ever scarcer cheap energy or of climate change do not destroy the landscapes we create, then the study of plant ecology in the urban environment is vital.

Acknowledgement Thank you to Dr. Ariel Lugo, forest ecologist, and Dr. Catherine Landis, botanist, for their thoughtful, probing, and insightful reviews that helped shape and enrich this chapter.

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[3] Some plant ecologists have called the ecological era of today the Homogocene claiming that there is a homogenization of biodiversity due to human alterations of the Earth and a unification of species that have long been separated around the globe. We would argue that their conclusions are based on taxa identification (lists of plant names) only and not on taxa richness, abundance, evenness, nor dominance which may argue for heterogeneity across the globe and across cities. We prefer the term Anthropocene to refer to the current era.

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Chapter 12
The Biological System—Urban Wildlife, Adaptation, and Evolution: Urbanization as a Driver of Contemporary Evolution in Gray Squirrels (*Sciurus carolinensis*)

James P. Gibbs, Matthew F. Buff, and Bradley J. Cosentino

Abstract Urbanization dramatically reduces levels of regional biodiversity, yet urban environments can serve as refuges for biodiversity because some biological stressors are more prevalent outside cities than inside. We evaluated whether urbanization can promote rare genotypes, focusing on gray squirrels (*Sciurus carolinensis*), which have genetically based color morphs visible to the naked eye. Combining data on 6681 occurrences of gray squirrels derived from an Internet-based, participatory research program (*SquirrelMapper*) and mined from an online image sharing platform (Flickr), we found the probability of the black morph increases with the extent of urban land cover. An internet-based game that crowdsourced search times of humans to find gray squirrels revealed a distinct camouflage advantage of gray morphs over black in early successional forests where hunting occurs but not in urban areas where hunting is prohibited. The black morph was strongly underrepresented (9%) within a sample of road-killed squirrels in contrast to its frequency (33%) among live squirrels in the same area, likely due to the black morph's greater conspicuousness on pavement, which in turn facilitates driver avoidance and thereby favors the black morph in cities where vehicles are the primary source of squirrel mortality. Together these processes can generate remarkably steep phenotypic clines along urbanization gradients and will likely continue to shape morphological

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evolution of the species given that hunting pressures are declining throughout the species' range while road traffic intensifies. This study suggests cities can serve as refuges for rare genotypes by neutralizing selective pressures that favor a widespread morph in the rural landscape while creating novel selective pressures against the widespread morph within urban areas.

Keywords Biodiversity · Citizen science · Contemporary evolution · Crowdsourcing · Geographical cline · Gray squirrel

12.1 Introduction

Urban ecosystems represent an extreme on the land use gradient of human impact where human-made structures dominate. Built ecosystems have generally not been a major focal point for biologists because they are primarily habitat for relatively few, very adaptable species that are in no danger of extinction. However, biodiversity of built environments is an important concern, for two reasons. First, most people now live in urban and suburban environments, and across the globe, human populations are shifting toward urban areas and away from natural and seminatural ecosystems [1]. Consequently, conservationists have an interest in built ecosystems being pleasant, healthy, and vibrant places for all people who will live there, for all the reasons biodiversity is important to human health. Notably, urban residents prefer higher species richness in urban green spaces (i.e., parks, wastelands, streetscapes) and agree that it creates far more livable cities, an attitude that prevails among different sociocultural groups, including people of immigrant backgrounds [2]. Second, many built ecosystems harbor a surprising variety of wildlife, species that cling to any oasis of "green" among all the concrete. Urban-adapting species frequently sustain themselves in part on the subsidies provided by urban areas, be it planted trees, intentional feeding stations, or the backyards across the vastness of suburbia that host a remarkable amount of wildlife [3].

Because urbanization dramatically reduces levels of regional biodiversity [4], urban areas have historically been of little interest to biologists [5–8]. Largely unrecognized, however, is that urban environments could serve as refuges for biodiversity given that many biological stressors are more prevalent outside cities than inside. Hunting-associated mortality of mammals is an example. Hunting is a well-documented driver of contemporary evolution of many traits in mammals (e.g., [9]) and is generally a prohibited activity in urban areas for reasons of public safety.

There is now strong evidence of adaptive evolution in urban systems due to altered resources and predation that can modify trophic (feeding and nutrition) linkages and selective pressures (phenomena that alter the fitness of living organisms within their environment) [10] and, in some cases, be strong enough to produce genetic differentiation between urban and rural populations (e.g., in foxes, [11]; damselflies, [12]; and passerine birds, [13]). For example, European blackbird (*Turdus merula*) males in Munich, Germany, exhibit reduced migratory behavior [14], urban sidewalk populations of the weed *Crepis sancta* have a higher proportion of

Fig. 12.1 The two morphs of the eastern gray squirrel (from Thornden Park, Syracuse, New York, Image credit: Elizabeth Hunter)

non-dispersing seeds than non-fragmented, rural populations [15], and urban populations of killifish (*Fundulus heteroclitus*) have significantly altered functional transcriptomes[1] (notably with genes related to cardiac toxicity) due to elevated PCB pollution [17]. All these examples of genetic adaptations to urban settings provide further argument for maintaining viable populations of species across their entire geographic range including built ecosystems. Nevertheless, investigations of evolution in urban landscapes are still surprisingly rare.

12.1.1 The Case of the Eastern "Gray" Squirrel in the City

The eastern gray squirrel (*Sciurus carolinensis*) is an interesting hypothesized case of contemporary evolution in response to urbanization. Gray squirrels are arboreal rodents native to eastern North America that thrive in both rural and urban areas [18] and exhibit color morphs (physical forms) easily recognizable to untrained observers (Fig. 12.1). The color morphs develop from variation in eumelanin and phaeomelanin production regulated by the melanocortin-1 receptor gene (*Mc1R*) [19]. The common gray morph is homozygous[2] for the wild-type allele (alternative forms of a given gene), whereas a deletion at *Mc1R* increases production of eumelanin in the skin and hair resulting in very darkly colored individuals [19] hereafter called *melanistic* or black morphs. The melanistic form predominates, for reasons

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[1] NIH: The human genome is made up of DNA (deoxyribonucleic acid), a long, winding molecule that contains the instructions needed to build and maintain cells. These instructions are spelled out in the form of "base pairs" of four different chemicals, organized into 20,000–25,000 genes. For the instructions to be carried out, DNA must be "read" and transcribed—in other words, copied—into RNA (ribonucleic acid). These gene readouts are called *transcripts*, and a *transcriptome* is a collection of all the gene readouts present in a cell [16].

[2] This means that the gray morph has two identical alleles (homozygous) for that gene.

as yet unknown, in many urban areas throughout the species' range [20] while having largely disappeared elsewhere [21] except in extreme northern parts of the species' range (mainly in Canada) where the black morph may retain a significant thermal advantage [22].

Hunting pressures and hunter behavior were first proposed to explain the selective disadvantage that the black morph evidently experiences across much of its range except in cities [23]; remarkably, this hypothesis has not been evaluated in the published literature for this widespread, abundant, and familiar species. The basis for the hypothesis is that outside of cities gray squirrels have been and remain avidly sought after by recreational hunters. For example, 360,000 gray squirrels were "harvested" in Illinois alone during 2010–2011 [24]. Old-growth forests, which originally dominated the gray squirrel's range, may possess visual refuges from hunters for black morphs (patches of deep shade, complex vertical layering of forest, and presence of coniferous trees with dark foliage), whereas the secondary forests that have almost entirely replaced them in eastern North America [25] consist of mostly deciduous tree species that lack vertical stratification and whose trunks and branches are much lighter-hued against which the black morph may be much more conspicuous to hunters. Hunters also exhibit a preference for novelty and hence may accelerate selection against melanistic individuals as the morph becomes rare in wild populations [26].

Urban environments may also present novel selective regimes. Contrasts of urban and rural populations of the closely related fox squirrel (*Sciurus niger*) [27, 28] indicate that predation is a negligible component of squirrel mortality in urban areas but a major one in rural areas, whereas "road kills" are by far the primary mortality agent of urban fox squirrels. Raptors, cats, and dogs do kill gray squirrels regularly in urban areas [29], but mortality on roadways due to automobile collisions is likely their primary source of mortality. Although a small proportion ($< 3\%$) of car drivers evidently intentionally swerve to kill small wildlife on roads [30], the vast majority swerve to avoid them. Given the remarkable similarity in hue of the gray morph to that of pavement, the propensity of automobile drivers to avoid killing squirrels, and the likely importance of road mortality as a driver of squirrel population dynamics in urban areas, the black morph may gain a selective advantage in urban areas owing to its conspicuousness on road surfaces which enables drivers to avoid it more frequently.

12.1.2 Urban Citizen Science

SquirrelMapper (*squirrelmapper.org*) was developed to engage the public (with an emphasis on urban residents) in "backyard-based" research about biological evolution based on mapping of color variants of the gray squirrel across urban-rural gradients of land use. Urban audiences are grossly underserved by most existing participatory research programs [31], which is unfortunate because the science-education nexus has real potential in urban areas [32]. Urban ecology is a strongly underrepresented component of environmental biology (just 0.4–0.6% of the ecology literature [5, 6, 8]), and evolution in urban environments has only recently become a focus of evolutionary biology [7, 33]. *SquirrelMapper*'s objective was to provide the public with an opportunity to integrate their understanding of both processes (natural selection) and outcomes (spatial pattern) of microevolution operating in human-dominated environments. To this end, *SquirrelMapper* linked squirrel morph occurrence as reported by participants with landscape features to enable understanding how morphological variation in squirrels is associated with landscape heterogeneity. *SquirrelMapper* also engaged research participants in a gaming/crowdsourcing[3] context to directly measure selection pressures potentially acting on morphs in rural and urban areas.

12.2 Methods

12.2.1 Squirrel Morph Occurrence Derived from Citizen Scientist Reports and Social Media

SquirrelMapper was piloted in 2010–2011 in Syracuse, New York area, a region where earlier studies of gray squirrel morph variation provided a conceptual foundation for the project [23, 29]. One component of *SquirrelMapper* was an Internet-based mapping system. Participants were mostly students recruited from local high schools, universities, and colleges via email and phone contacts with their instructors. Participant reports included the number of squirrels observed, date of observation, and squirrel morph (gray, black, or others) and whether a squirrel was alive, road-killed, or hunter-killed. Squirrel locations on *SquirrelMapper*'s mapping interface were secured via Google Maps JavaScript API. Each squirrel reported was automatically linked to the 2001 National Land Cover Dataset land use categories (resolution 30 m) to permit understanding landscape correlates of geographical variation in morph frequencies in the region studied [34].

In subsequent years, *SquirrelMapper* has attracted a large following of citizen science contributors throughout the species' native range, and these contributions enabled us to look at geographical correlates of morph distribution. We complemented *SquirrelMapper* observations with data on squirrel color morph mined from Flickr, a Yahoo-owned image database consisting of over six billion images with geographic location available for most images. To do so we developed code from the Python programming language that queried the Flickr image bank for metadata for images with the associated tag "squirrel" within specified geographical "bounding boxes" (generally 1 km^2 blocks) while "walking" across the entire range of the gray squirrel. For each image identified within a given bounding box, we harvested date and time posted, latitude, and longitude. Because the image tag "squirrel"

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[3] Crowdsourcing is the act of engaging a large number of people in a common goal, in this case the gathering of information.

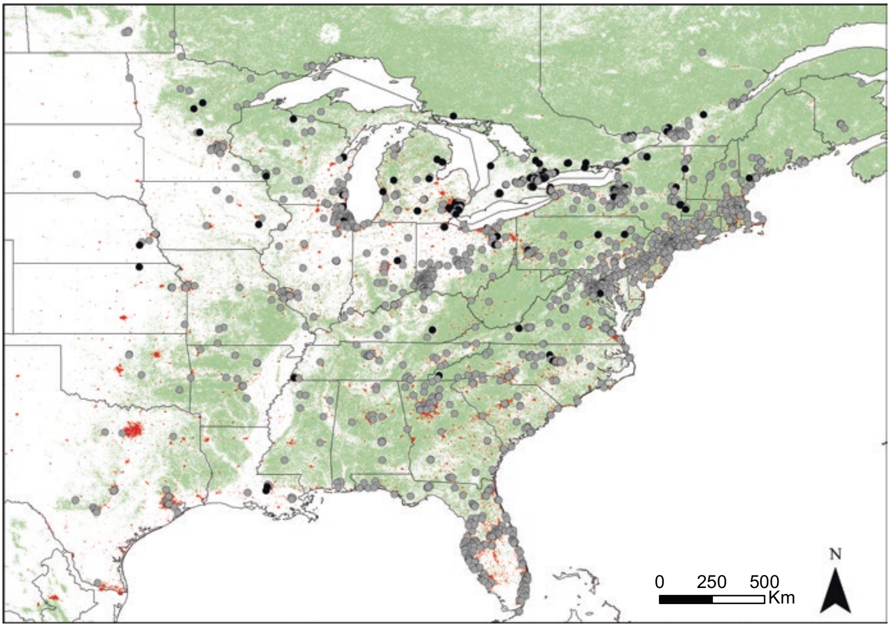

Fig. 12.2 Map of forest cover (green), urban cover (red), and squirrel observations (circles; $n = 6681$) from *SquirrelMapper* and Flickr. Circle fill represents gray and black color morphs

generated many images unrelated to gray squirrels, we developed separate code to call each image's URL into a pop-up window and allow a human viewer to classify the image, retaining only those of gray squirrels.

We combined squirrel observations from *SquirrelMapper* ($n = 2785$) and Flickr ($n = 3896$) made through 2014, resulting in a combined dataset of 6681 records (Fig. 12.2). We created a regular grid with 5 × 5 km cells covering the spatial extent of all squirrel observations and quantified the proportion of urban cover, mean annual air temperature, and mean elevation for each grid cell. Urban cover was classified with a 250 m land cover dataset for North America in 2010 [35], and elevation was quantified with a 1 km dataset for North America in 2007 [36]. We used the Climatic Research Unit time series version 3.10 to quantify mean annual temperature for 1901–2009 [37].

We then used a path analysis, a form of regression analysis that identifies causal connections between sets of variables, to examine how the distribution of melanistic squirrels was related to urban cover, elevation, and temperature. Path analysis allowed us to examine hypothesized direct and indirect effects of environmental variables on the occurrence of melanistic squirrels. The model included direct effects of urban cover, elevation, and temperature on melanism,[4] as well as indirect

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[4] From Merriam Webster—an increased amount of black or nearly black pigmentation (as of the skin, feathers, or hair) of an individual or kind of organism.

effects of elevation mediated by urban cover and temperature. We also included a covariance term to account for a potential correlation between urban cover and temperature.

We used the *lava* package in R to fit the path model [38, 39]. The *lava.tobit* package was used to define color morph as binary and to fit a model for melanism with a probit link[5] [40]. Temperature and elevation were rescaled so that the variances of observed variables were similar in magnitude. The model was fit with maximum likelihood, and we estimated robust standard errors to account for the clustering of squirrel observations within 5 km grid cells. We first fit the model with all squirrel observations included. We then fit a second model with observations only from the northern part of the species' range (n = 3867), including New England and mid-Atlantic states in the United States (CT, DC, DE, MA, MD, ME, NY, NJ, NH, PA, RI, VA, VT, WV).

12.2.2 Measuring Selection Differentials Through Interactive Games

A complementary component of *SquirrelMapper* was an interactive " Squirrel Hunt" game that enabled users to compete to locate squirrels on different visual backgrounds and thereby measure the selection coefficients (survival probabilities) of the two morphs against different forest backgrounds. On each image was placed a "pseudo-squirrel" or cutout of the image of the back of a squirrel that was captured as part of the same image scene and then excised (to control for optical conditions when each image was taken) and placed at random on a tree trunk in each scene (Fig. 12.3). Each gray and black "pseudo-squirrel" was placed in exactly the same location for separate viewings of each image (direct pairing of morphs within scenes). In this manner squirrels were added to 20 independent images each of old-growth forest (from the last remaining old-growth patch in the region situated at Green Lakes State Park, Fayetteville, New York, adjacent to Syracuse), second-growth forest in rural areas near the city of Syracuse, and urban forest in public parks within the city limits and presented to participants in random order. The time between the first display of each image and the participant clicking on the "pseudo-squirrel" is logged by a web-based interface. This crowdsourcing approach, based on techniques used by military scientists developing camouflage systems [41], exploited the same visual system as actual hunters in the field and thereby directly measured hunter-related selection pressures in a biologically meaningful way, that is, time to detection is equivalent to opportunity to seek cover via an evasive maneuver by squirrels and hence directly correlates with survival probability in a hunting context. Confidence intervals ($\alpha = 0.05$) were constructed to contrast differences in search times (black minus gray in the same image) among the three forest types

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[5] The purpose of the probit (*prob*ability un*it*) model is to estimate the probability that an observation with particular characteristics will fall into one of two categories (gray or black).

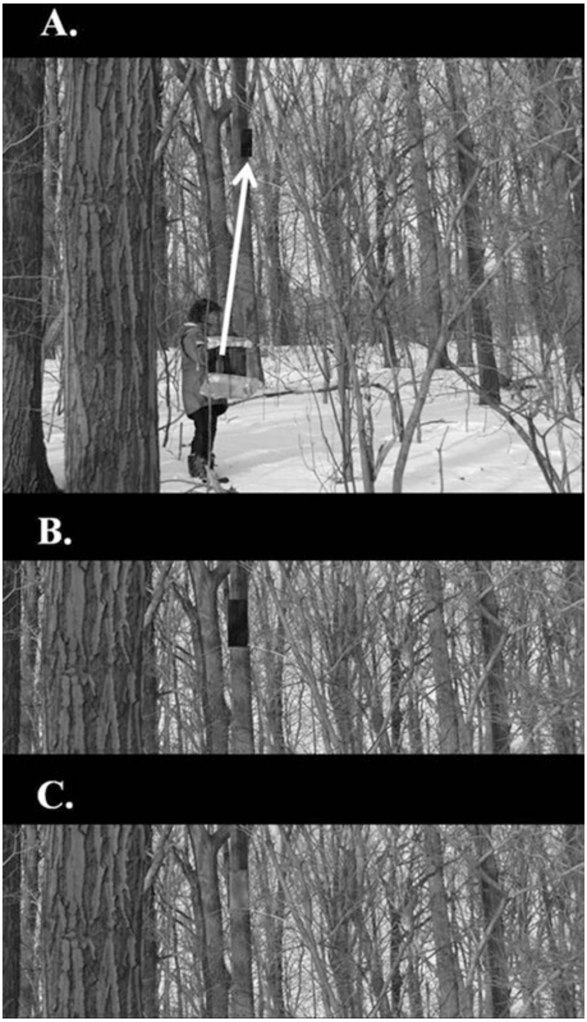

Fig. 12.3 Method adapted from military crypsis research for developing visual experiments for measuring selection differentials due to hunting on black versus gray morphs. A photograph of a sample forest scene (**a**) was captured along with a set of museum specimens of both morphs squirrels in the same image (three gray and three black morphs in alternating order mounted vertically and side by side on the board held by the field assistant). A square "cutout" of the back of a squirrel was taken from one squirrel specimen presented in the image, and the cutout or "pseudo-squirrel" was then transferred to a randomly chosen location (≥5 m above ground level) in the closest tree. The lower section of the image was then removed (**b**) with only the background and the "pseudo-squirrel" included. The middle image (**b**) features a black "pseudo-squirrel," whereas the lower image (**c**) features a gray "pseudo-squirrel" clipped from the same panel of squirrels (in **a**) and located in exactly the same location as the paired black "pseudo-squirrel" (in **b**). Such paired images were then shown to players of the "Squirrel Hunt" internet-based game who were required to click on the "pseudo-squirrel" as soon as they could find it after first viewing the image

(old-growth forest, second-growth forest, urban forest) with observer as the replicate (*n* = number of observers) and the response variable being the grand mean of differences between each observer's search time (black minus gray) in each scene averaged across the 20 independent scenes of each visual environment.

During the study it became apparent that differential susceptibility to roadkill might also serve as a selective force favoring the black morph in urban areas. To evaluate this hypothesis, ratios of morphs within a sample of road-killed squirrels were contrasted with a sample of live animals both observed within the same urban area where squirrel reporting had been particular intensive (Syracuse's "University Neighborhood" as bounded by East Genesee St., Comstock Ave., Westmoreland Ave., and East Colvin St.) to provide a means of measuring the potential selection differential between the two morphs due to road mortality. To further evaluate this hypothesis, crypsis[6] of actual squirrels relative to road surfaces and hence vulnerability to roadkill were also quantified following a method devised for squirrels by Kiltie [42] in which three representative individuals from each of the two morphs (*n* = 6) were obtained from a museum collection, placed side by side on pavement under dry/sunny conditions, dry/cloudy conditions, and wet/cloudy conditions and photographed. Crypsis was measured as the average absolute difference between the proportional representation of pixels in each of 256 intensity classes for each of the six squirrels versus the pavement background in each of three images. Crypsis values were then subjected to a linear mixed effects model with weather condition (dry pavement/sunny, dry pavement/cloudy, wet pavement/cloudy) and morph as fixed effects and individual squirrel specimen included as a random effect to account for repeated measures on individuals [43] using the lme4 package in R [44].

12.3 Results

During a 1-year pilot of *SquirrelMapper* focused in Syracuse, New York, during which 1447 squirrels were reported by 181 contributors, ca. 65% of the squirrels mapped were of the black morph at the urban core (within 1 km of the city of Syracuse's geographical center), with the black morph declining to 0 within 15 km from the city center (Fig. 12.4). More specifically, the prevalence of the black morph increased in direct proportion to the intensity of urban development of the landscape (Table 12.1). In the broader geographic range of gray squirrels, probability of melanism was related to temperature, elevation, and urban cover based on our path analysis (Fig. 12.5). Black morphs were most likely to occur in areas with cool annual temperature, at high elevation, and in urban areas (Fig. 12.6). Temperature was the strongest predictor of melanism when we included all squirrel observations in the model, whereas urban cover was the most important predictor in the model focusing on individuals from New England and the mid-Atlantic (Fig. 12.5).

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[6] The ability to avoid observation or detection.

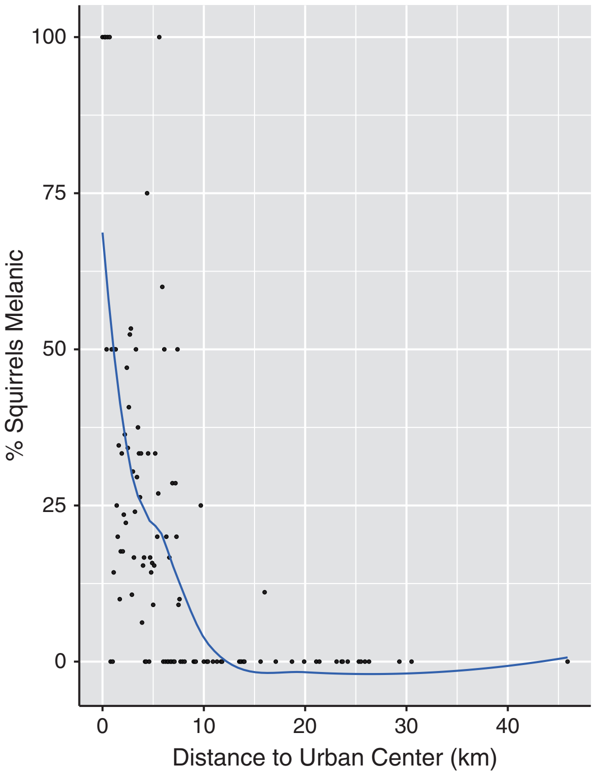

Fig. 12.4 Relationship between distance to urban center (Clinton Square, City of Syracuse, New York) and frequency of gray versus black morph of the gray squirrel. Line represents a running three-point average

Table 12.1 Frequency of occurrence of gray versus black morphs of the eastern gray squirrel in relation to landscape context in the vicinity of Syracuse, New York

Landscape context	*n*	% black
Urban—High-intensity development	45	44.4
Urban—Medium-intensity development	205	28.8
Urban—Low-intensity development	441	23.8
Urban—Open space	408	25.7
Rural	348	13.2

n = number of squirrels observed in that land use category (based on reclassification of National Land Cover Dataset land use categories, 2001 data, [34])

Based on performances by *n* = 56 participants in the Squirrel Hunt "game," observers took more time to locate the black morph in scenes of old-growth forest, whereas the black morph was located faster than the gray morph in secondary forests (Fig. 12.7). These results indicate the black morph was more conspicuous than the gray morph in secondary forests, whereas the reverse was true in old-growth forests. There was no difference in the time to locate the two morphs in urban forest scenes.

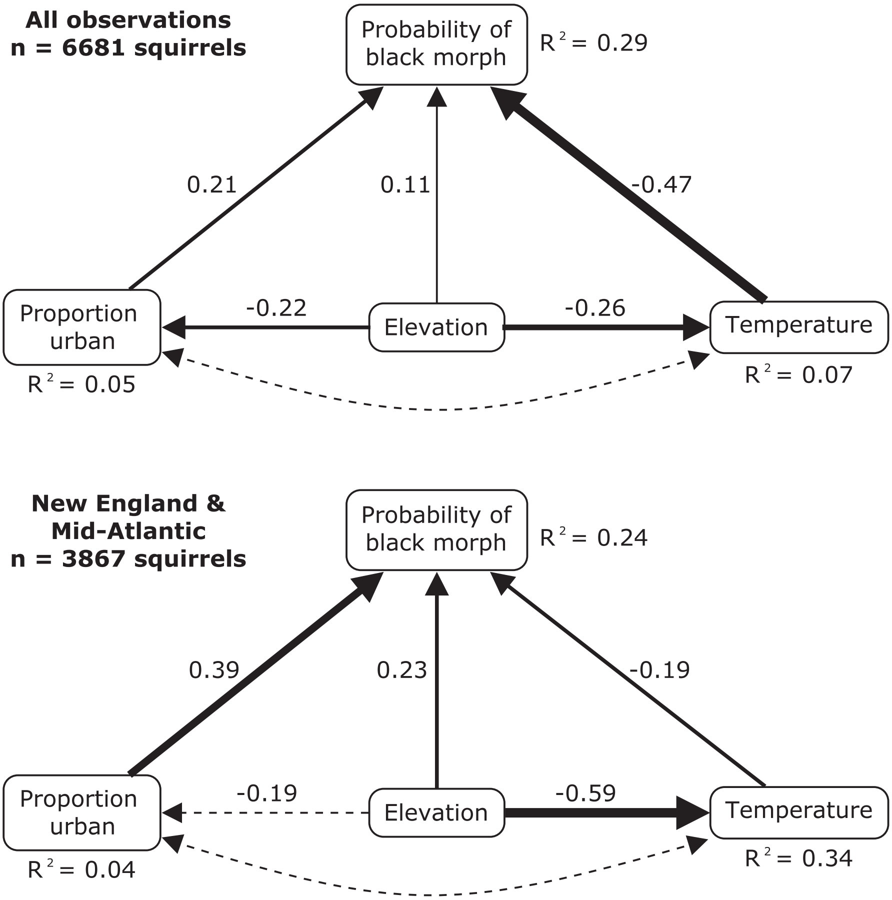

Fig. 12.5 Path analysis of color morphs for eastern gray squirrels in the United States and Canada. Models included all individuals (top) or a subset of individuals from New England and mid-Atlantic states in the United States. Single-headed arrows represent regressions, whereas double-headed arrows represent correlations. Solid lines show significant pathways at $P < 0.05$, and dashed lines represent nonsignificant pathways. Arrow thickness is scaled to the magnitude of standardized regression coefficients which are shown for each pathway

Contrasts of morph ratios within a sample of road-killed and living animals in the same area of Syracuse, New York, indicated that 8.7% of 23 road-killed squirrels observed were of the black morph, whereas 32.9% of 629 live squirrels reported in the same area were of the black morph (G-test: $G_{adj} = 7.2$, df = 1, $P = 0.007$). Mean absolute difference across the 256 intensity classes for black and gray morphs placed on wet and dry pavement (intercept: $t = 11.9$, $P < 0.001$) revealed that only morph contributed ($t = -5.0$, $P = 0.002$) as a significant effect, whereas background condition did not (clear sky/dry pavement conditions versus cloudy sky/dry pavement: $t = -1.5$, $P = 0.149$; cloudy sky/wet pavement versus cloudy sky/dry pavement conditions: $t = -1.517$, $P = 0.151$). The gray morph had, on average, a much lower

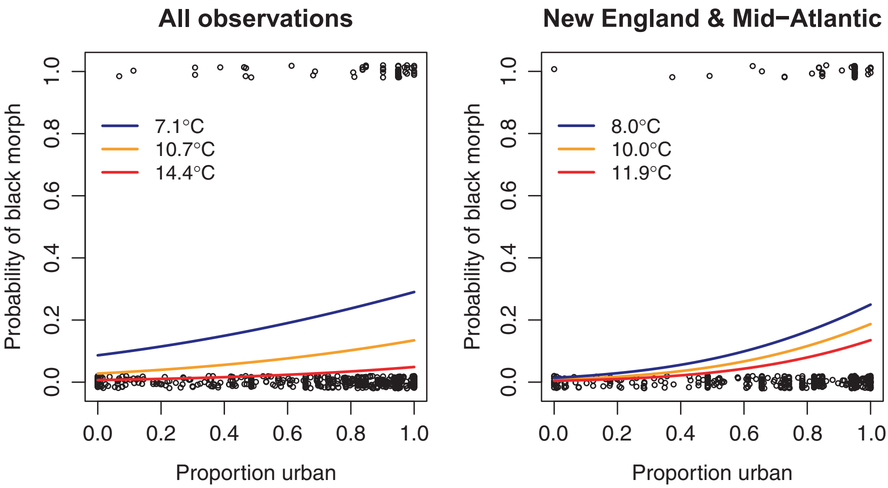

Fig. 12.6 Relationship of occurrence of the black morph to urban cover throughout the native geographic range of eastern gray squirrels. Best-fit lines represent effects of urban cover on the probability of the black morph at different annual mean temperature (mean ± 1 SD) based on regression coefficients from path analyses (Fig. 12.4). Circles represent a random selection of 500 squirrel observations classified as black (1) or gray (0)

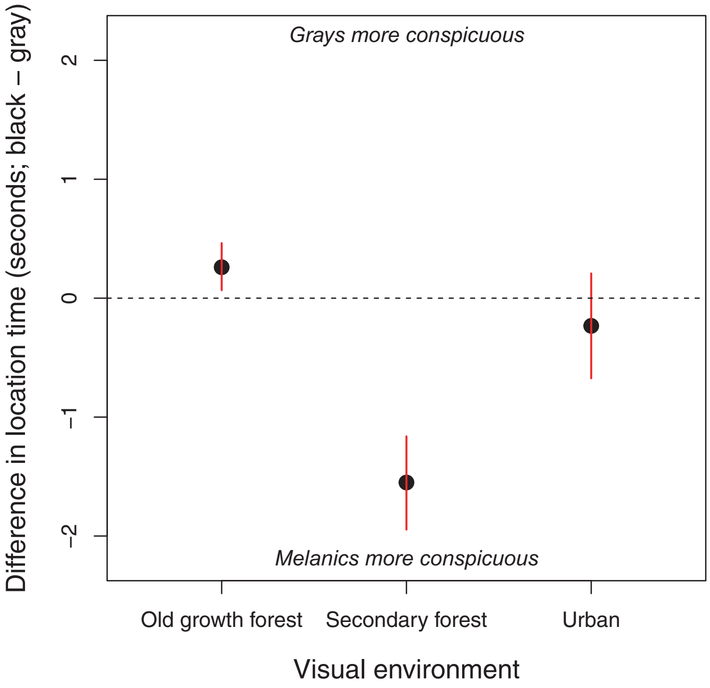

Fig. 12.7 Mean difference in time to locate black and gray squirrels in old-growth forests, secondary forests, and urban environments. Error bars represent 95% confidence intervals

mean absolute difference across the 256 intensity classes relative to pavement (i.e., was more similar to) by about an order of magnitude: clear sky/dry pavement conditions for black = 0.02 versus gray = 0.008; cloudy sky/dry pavement for black = 0.023 versus gray = 0.013; and cloudy sky/wet pavement for black = 0.018 versus gray = 0.011.

12.4 Discussion

This study using a participatory research approach enabled accumulation of a dataset at a spatial scale, sampling density and time frame likely infeasible using a traditional "experts only" model (cf [45, 46]).[7] A participatory research approach combined with crowdsourcing also enabled direct measurement of selection coefficients at a level of precision difficult to obtain in any other way because a large number of viewers were available, and there was compatibility between the visual systems and motivations of both game players and the actual selection agent at work in nature, that is, hunters in the field. Our results strongly suggest divergent selection for crypsis operates across urbanization gradients, with hunting favoring gray morphs in rural areas and roadkill favoring black morphs in urban areas. These altered selection regimes associated with urbanization and forest disturbance likely cause what may be one of the sharpest geographical clines[8] yet reported for any mammal (cf [47]). More generally, the study indicates that urban areas can serve as refuges for rare genotypes[9] and also create novel and contrasting selection regimes for species distributed along urban-rural gradients.

It is notable that the width of the geographical cline in gray squirrel phenotype frequencies[10] observed in Syracuse, New York, is comparable to dispersal distance of the species (4–5 km) [48]. This suggests extremely strong and divergent selective pressures at the cline's center which in this case directly overlaps with an urban/rural land use transition [49]. Moreover, the very existence of a black morph-dominated urban "island" population (which in Syracuse has a diameter of only about 6 km) suggests that selection pressures must be extremely strong to maintain habitat-specific phenotypes [50]. The urban, black morph-dominated population likely receives immigrants from gray morph-dominated populations from all directions yet has persisted for decades (>25 years since first documented by Tomsa [23]).

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[7] Cf means compare findings from this work with those of the referenced authors.

[8] A spatially varying gradation of one or more characteristics within a species especially between adjacent populations.

[9] Organisms with rarely occurring combinations of alleles (gene variations).

[10] Number of occurrences of the set of observable characteristics of individuals, resulting from the interaction of their genotype with the environment.

Restricted dispersal combined with historic geographic subdivision could establish the clinal pattern observed if population density or gene flow was low [51]. Urban "black squirrels" might represent a genetic anomaly associated with multiple independent introductions by city dwellers of the black morph as a novelty in decades past (e.g., [52]) that are unable to "escape" from urban areas. However, gray squirrels are extremely abundant animals in both urban and rural areas [53]. They also have high potential for long-distance dispersal [48]. Moreover, major barriers to dispersal of squirrels from urban to rural areas would have to exist; otherwise the morph would have disseminated into areas adjacent to cities long ago given the length of time since many introductions are known to occur [52]. Yet no such physical barriers to dispersal are obvious in Syracuse and many other moderate-size cities; rather, landscape permeability to squirrel dispersal likely increases at the city edge due to coalescing tree cover along an axis outward from the city center [54].

Alternative hypotheses about factors that might explain the sharp geographical cline observed remain untested. The black morph has greater capacity for non-shivering thermogenesis and loses less heat than the gray morph, which likely explains why the black morph was more likely to occur in colder areas. Yet thermal advantage is unlikely to explain the prevalence of the black morph in urban areas because cities generate a "heat island" some 2–3 °C higher than surrounding areas [55] (see Chap. 7), and the association between the black morph and urban areas actually became stronger when we restricted our path analysis to squirrel observations from cool, northern areas. Perhaps despite a warmer ambient environment, squirrels may be more exposed in urban areas, and resources for building adequate nests to overwinter may be more limited in cities. This is a hypothesis yet to be evaluated but one that could be, with temperature-based radiotelemetry tags attached to urban and rural squirrels. Last, urban squirrels are faced with a high degree of acoustic noise [56], and it is possible that noise pollution reduces scope for auditory communication, which is well developed in gray squirrels [57], thereby shifting communication to domain of visual signaling in which black morphs might have an advantage, although our assessment of visual conspicuity suggests equality between morphs in urban forests (at least to human observers).

Looking into the future, cities could play an important role in recolonization by the black morph of the larger peri-urban landscape. More specifically, strong, long-term declines in hunting participation due to social trends in rural areas have been reported [58]. If hunting pressures near cities continue their decline and forest regeneration continues, cities may ultimately serve as a propagule source for repopulating adjacent rural areas with the black morph that likely dominated in the pre-colonial period throughout much the species' range [21]. Whatever happens some cities like Syracuse, New York, are currently serving as a genetic refuge for the gray squirrel and reservoir of genetic variation for future adaptation of gray squirrels to a changing environment.

12.5 Conclusion

Urbanization is the fastest-growing and most irreversible form of land use change. The physical changes associated with urbanization have lasting ecological consequences such as the loss of species richness. Yet for species persisting in urban landscapes, urbanization can shape life-history traits and demography as a result of altered natural selection regimes. Eastern gray squirrels, wide-ranging arboreal rodents that exhibit coat color polymorphism ranging from gray to melanistic (black morph), are a case in point. Historical records suggest melanistic squirrels were once the more common variant inhabiting pre-colonial forests, but in recent decades, melanistic squirrels have persisted mostly only within urban centers. Our study, which integrated citizen science-based sampling of phenotypic variation of coat color in gray squirrels with exploration of microevolutionary forces that shape genotypic variability across urban-rural gradients, revealed that human-modified landscapes foster a novel suite of selection pressures that maintain color polymorphism in gray squirrels along urban-rural gradients. Notably, cities may now be playing an important role in recolonization by the black morph of the larger rural landscape as hunting pressures near cities continue their decline and forest regeneration continues. In this sense, many cities in the gray squirrel's native range may be serving as a reservoir of genetic variation for future adaptation of the species to its ever-changing environment.

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Chapter 13
Environmental Justice in the Urban Environment

Myrna H. P. Hall and Stephen B. Balogh

Abstract This chapter introduces students to the topic of environmental justice. Environmental justice (EJ) is the fair treatment and meaningful involvement of all people with respect to environmental contamination or degradation. The call for EJ stems from a history of discrimination where both corporate entities and governments have selected locations for locally undesirable land uses (incinerators, sewage treatment plants, bus barns, etc.), known as LULUs, in neighborhoods where the population was majority nonwhite race and/or economically poor. This history means that these communities have disproportionately resided in some of the most toxic urban environments or in rural areas where raw materials for our cities' economic life are extracted or where urban wastes are frequently disposed. The US Environmental Protection Agency's Office of Environmental Justice was formed in 1993 to help communities fight institutionalized racism. Case studies and tools for assessing EJ violations are presented, and factors influencing public response to environmental risk are reviewed.

Keywords Environmental justice · Environmental racism · NIMBY · LULU

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13.1 Introduction

The US Environmental Protection Agency defines environmental justice (EJ) as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. *Fair treatment* means that no group of people, including a racial, ethnic, or a socioeconomic group, should bear a disproportionate share of the negative environmental consequences resulting from industrial, municipal, and commercial operations or the execution of federal, state, local, and tribal programs and policies. *Meaningful involvement* means that: (1) potentially affected community residents have an appropriate opportunity to participate in decisions about a proposed activity that will affect their environment and/or health; (2) the public's contribution can influence the regulatory agency's decision; (3) the concerns of all participants involved will be considered in the decision making process; and (4) the decision makers seek out and facilitate the involvement of those potentially affected." In sum, the goal to be achieved is environmental justice for all communities and persons, when everyone, regardless of race, culture, or income, enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment in which to live, learn, and work [1].

13.1.1 The Environmental Justice Movement

The environmental justice movement represents a diverse, multiracial, multinational, and multi-issue coalition and calls for equal protection of all people from environmental harms, regardless of their race, ethnicity, origin, and socioeconomic status. As with other social movements (i.e., antiwar, civil rights, women's rights, etc.), the EJ movement emerged as a response to industry and social practices, policies, and conditions that many people judged to be unjust, unfair, and illegal. It emerged from grassroots activism and organizations and penetrated national and international arenas. The EJ movement was thus a fusion of the racial critique of civil rights activists' and the antitoxins push of the environmental movement.

13.1.2 The History of the Environmental Justice Legal Framework

In 1979 Linda McKeever Bullard, a Houston attorney, agreed to represent a group of Houston residents who wanted to stop the installation of a municipal landfill in their neighborhood. This lawsuit, known as Bean v. Southwestern Waste Management Corp., was the first time in the United States that the defense of racial discrimination was used against the siting of a waste facility under the civil rights laws. The middle-class neighborhood situated in suburban Houston seemed an unlikely place to establish a landfill garbage dump but for the fact that it was more than 82% black. Dr. Robert Bullard, attorney Bullard's husband, having completed two master's degrees, one in government and the other in sociology, and more recently a Doctorate of Sociology was called upon to conduct a study of existing waste facilities in the city of Houston [2]. What he and his fellow researchers found was that all five city-owned garbage dumps, six of the eight city-owned garbage incinerators, and three of the four privately owned landfills were sited in black neighborhoods, although blacks made up only 25% of the city's population [2]. For Dr. Bullard this was the beginning of a long academic and activist career exposing the injustices of environmental racism. In his words, "it was a form of apartheid where whites were making decisions and black people and brown people and people of color, including Native Americans on reservations, had no seat at the table" [3]. He expanded his work to look at environmental racism across the entire American South where he found time and time again a larger burden of toxic sites had been built in African-American communities than in white communities, which meant greater health risks to blacks than to whites. From this work he produced his first book in 1990, *Dumping in Dixie: Race, Class, and Environmental Quality*, in which he documented his findings and signaled that a grassroots environmental justice movement was underway [4].

Three years earlier, in 1987, the United Church of Christ Commission for Racial Justice had conducted the first national study on the topic of toxic waste and race in the United States. Their report was authored by the Reverend Charles Lee of the United Church of Christ [5]. The commission found race to be the single most important factor in the siting of toxic waste facilities. In 1990 the faculty at the University of Michigan formed the "Michigan group," a group that included Dr. Bullard, Rev. Lee, and Dr. Bunyan Bryant of the University. Their mission was to discuss research findings on environmental racism and to bring their findings to government officials. They lobbied for meetings with both Department of Health and Human Services (HHS) and US Environmental Protection Agency (EPA) administrators and staff (the EPA had been created in 1970 under President Nixon). Secretary Louis Sullivan of HHS never responded to their invitations, but meetings with William Reilly, acting EPA administrator under President George HW Bush, led to the creation of a Workgroup on Environmental Equity. This later became the Office of Environmental Equity.

During this time interval, in 1991, the First National People of Color Environmental Leadership Summit had been held October 24–27 in Washington, DC. Seventeen principles of environmental justice were drafted and adopted [6]. Their major finding was that some individuals and groups receive less protection than others because of their geographic location, race, and/or economic status and that over the years disparities had been created, tolerated, and institutionalized and that the existing environmental policies should regulate, manage, and distribute risks among those who were receiving the benefits of these facilities. One of those most influential at this meeting was Dr. Bullard, now considered the father of the EJ movement, whose research showed that with respect to EPA:

- Average penalties against polluting companies were lower in low-income communities.
- Abandoned hazardous waste sites took longer to be placed on the National Priorities List (NPL) for cleanup.
- When finally included on the NPL, a toxic site cleanup took longer to get underway in these communities.

In minority neighborhoods, the EPA chose “containment” more frequently than permanent treatment to eliminate the wastes or get rid of the toxic substances. The National Environmental Justice Advisory Council (NEJAC), a federal advisory committee, was established by charter on September 30, 1993, to provide independent advice, consultation, and recommendations to the administrator of the US Environmental Protection Agency. On February 11, 1994, the White House, under President Bill Clinton, issued Executive Order 12898 on Federal Actions to address environmental justice in minority and low-income populations. The order stipulated that “each Federal agency shall make achieving environmental justice part of its mission by identifying and addressing, as appropriate, disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations” ([7], p. 1). The goal of environmental justice was and is to identify and address unfairness and inconsistency in environmental matters. A year later in January of 1994, acting director of the EPA, Carol Browner, wrote:

> We now believe that the remedies we utilized to improve environmental quality, during the past two decades, have not benefitted all communities equally. People of color and low-income communities often perceive a higher level of environmental risk than the majority population, especially related to the areas of hazardous waste exposure, disposal, and containment. Some of these communities bear a disproportionate share of the nation's air, water, and waste-contamination problems. We are committed to addressing these concerns and are assuming a leadership role in environmental justice initiatives in order to improve the environmental quality for all residents in the United States. More than ever, businesses, communities, and federal, tribal, state and local governments are coming to realize the link between environmental justice, sustainable development, economic development, and community empowerment. To achieve the ultimate goal of environmental justice, it is critical that these parties work together, in partnerships, to effectively change the direction of current policies. To succeed, environmental justice will require that managers, in conjunction with all stakeholders, have a better and more sophisticated understanding of the environment. The opportunity to make these changes is the challenge facing us today [8].

13.2 Environmental Justice Goals

The following guiding principles and concepts have served to shape the Environmental Protection Agency’s Environmental Justice Program and initiatives. They are:

- *Equal protection* is the objective.
- *Early and meaningful involvement* of the affected community is essential.
- A community's *perception* is its reality.
- Solutions require all stakeholders to participate at the table.
- Meetings must be convenient for the affected community.
- Look at existing environmental regulations, statutes, and policies to incorporate and consider EJ.
- *Environmental justice is a matter of fairness* [2].

Let's look for a moment at what *equal protection*, *early and meaningful involvement*, and *perception* actually mean.

13.2.1 Equal Protection

Equal protection implies that all people regardless of race or income level will be treated the same when decisions are being made as to the siting of necessary yet locally undesirable facilities. These are often called locally undesirable land uses or LULUs and include but are not limited to:

Recycling plants	Power plants	Transportation routes
Radioactive waste disposal sites	Garbage truck depots	Incinerators
Toxic facilities and factories	Landfills	Sludge facilities
Research labs	Waste management facilities and waste transfer stations	
Correctional facilities	Airports and other transportation hubs	

These are the things to which people respond with emotional outcries of "Not in my backyard!" or NIMBY. In 2017, rather than focusing on *types* of facilities and their location, the EPA selected the following *environmental indicators* for inclusion in their EJ screening tool. These measures of risk apply to existing facilities:

- Air pollution:
  - PM2.5 level in air
  - Ozone level in air
  - NATA air toxics:

    Diesel particulate matter level in air
    Air toxics cancer risk
    Air toxics respiratory hazard index

- Traffic proximity and volume: Amount of vehicular traffic nearby and distance from roads
- Lead paint indicator: Percentage of housing units built before 1960, as an indicator of potential exposure to lead

- Proximity to waste and hazardous chemical facilities or sites: Number of significant industrial facilities and/or hazardous waste sites nearby and distance from those including:
  - National Priorities List (NPL) sites
  - Risk Management Plan (RMP) facilities
  - Hazardous Waste Treatment, Storage and Disposal Facilities (TSDFs)
- Wastewater discharge indicator: Proximity to toxicity-weighted wastewater discharges

These were selected based on several factors that included the spatial resolution of the environmental data (air, water, age of housing stock, road categories, etc.) available, i.e., how small a geographic area the data covered; the geographic coverage of the data, i.e., if available for the entire United States; whether there was evidence of an EJ concern with respect to these pollutants, i.e., disparity between different demographic groups has been previously indicated; and finally, the public health significance of each.

As a result of EJ efforts, permitting agencies must now consider who benefits and who bears the cost of those facilities and whether one group will bear a disproportionate share of the burden. The *burden* is measured as a decline in quality of life and must be borne across the entire community, not just one demographic group, hence *equal protection*. The cost is really the degree to which a community's quality of life, including health, is diminished. According to Rasmussen, "Part of the uniqueness of the environmental justice movement is the focus on injustice as a collective experience. Consequently, those in the movement strive for the actual pursuit, promotion, and establishment of better living conditions in the midst of collective entities, both human and non-human" [9]. Communities have been coming up with quality of life indicators since the 1960s [10]. Intended to engage citizen participation in building healthier, more sustainable communities, these efforts also have identified many of the following list of amenities that make a place a good place to live. They include among others:

1. Housing: home ownership, affordable homes and rental properties, appreciating property values
2. Education: good and safe public education
3. Mobility: transportation alternatives and efficient flow of traffic
4. Health care: access to good and affordable health-care facilities and services
5. Employment: individuals having jobs and communities having low unemployment rates
6. Recreation: well-designed and accessible public spaces, open spaces, parks, greenways, and recreational facilities
7. Environment: clean, green and with minimum pollution, resource- and energy-efficient residential and commercial buildings, *environmental justice*
8. Economics: economic vitality and affordable products and services, local business owners, vibrant downtowns

9. Public safety: least possible exposure to crime, pollution, threat of disease, and disasters
10. Equity and civic engagement: ability for residents, community groups, and the private sector to participate in planning and development efforts
11. Disaster resistance: disaster-resistant housing, employment, transportation, and public facilities

LULUs detract from quality of life with a variety of negative impacts. These can include:

- High incidence of health problems—asthma, cancer
- Air pollution, e.g., a bus transit facility
- Lead poisoning
- Noise
- Lack of open spaces and parks
- Disinvestment in the neighborhood

Not all environmental justice issues revolve around future siting of undesirable facilities or industries and the harmful toxins, noise, or other environmental disturbance associated with such entities, but more often they are focused on a legacy of contamination from the siting of such facilities in the past or, as we describe here, a legacy of disinvestment that affects the metabolism of these neighborhoods, requiring considerably more energy investment from people in terms of distance to travel for services or to heat or cool aging unimproved houses. The people who now live in proximity to noxious sites are there because either (1) people who could afford to leave the area did so and the housing stock lost value making it more affordable to the poor or (2) those areas of the city suffered from disinvestment under the 1930s racially motivated home mortgage loan policies of the Federal Home Owners' Loan Corporation Association (HOLC). Established during the Great Depression as part of President Franklin Roosevelt's New Deal, the program was designed to provide home mortgage loans to people, who "through no fault of their own" were having trouble making their mortgage payments. The HOLC would purchase the mortgage from lenders, who profited, and homeowners benefitted from a longer time period to pay off the loan and lower rates. The government asked 239 cities to submit color-encoded maps of neighborhoods to determine economically safe areas to invest in homeowners, where:

Green = "best" places to provide government-backed loans
Blue = "still desirable"
Yellow = "in decline"
Red = "hazardous"

"Hazardous" really meant that local lenders believed the people who lived there were credit risks but which, in fact, was based solely on race as indicated by comments on the few maps that remain. (The blatantly racist maps were supposed to have been destroyed, but some have surfaced in recent years giving evidence to the motivation.) These were neighborhoods occupied predominantly at that time by

African-Americans, Catholics, Jews, and Asian, Eastern European, and Southern European immigrants. In most cities, due to this period of disinvestment, these neighborhoods, located in the urban core, are the least expensive neighborhoods and hence are occupied by the least economically secure predominantly African-Americans.

These neighborhoods often suffer from lack of facilities, such as fully functioning grocery stores. This, too, is also seen as an environmental justice issue, but there is no legal mechanism under the 1994 Executive Order by which this can be addressed. Nonetheless the lack of affordable food and fresh produce, otherwise known as a food desert (see discussion in Chap. 14), is another way that health and well-being of urban poor and minority communities are impacted [11]. Similarly, abandoned houses, especially those being used for illegal activities, or abandoned lots with legacy dumps also diminish quality of life in these neighborhoods [12]. Furthermore, the housing stock of these generally older neighborhoods dates to a time when leaded gasoline and lead-based paints were still being used. This means that inside walls and window sills and outside soils are heavily contaminated with lead. Lead dust brought in on shoes from the yard has been documented on the floors of these residences [13]. This has led to a high incidence of elevated blood lead levels in children from these communities and this has been shown to cause behavioral issues and slowed learning ability [14]. It is yet another example of an EJ issue that was not explicitly covered by the original Executive Order.

Environmental justice is not just an urban issue. In fact, many mining and other extractive industries have left rural communities with degraded environments and serious health issues (e.g., coal mines of West Virginia). The materials from these sites, however, are usually headed to cities to be used in industrial production or to generate electricity for urban homes and businesses. Thus, from a system's perspective, people living in rural environments whose health is degraded by exploitation of resources destined for cities or by wastes derived from cities should also be considered as part of the urban environmental justice issue. As seen in Chaps. 2, 7, and 10, the materials required for the metabolism of a city can come from great distances. Likewise, a city's waste products often travel long distances through rural areas to a final landfill, or move downstream to rural areas, or are even shipped overseas to poor countries willing to take on the toxic material in exchange for dollars.

13.2.2 Early and Meaningful Involvement

Early and meaningful involvement means that community members are consulted at the beginning of considerations for siting a LULU. Not only is information provided to them but also conversations must be structured to hear their views on what they will and will not tolerate and what amenities could be incorporated into the design that would actually enhance quality of life in the neighborhood. Too often decisions are made to implement a LULU in a neighborhood and only after the fact is the community informed. This is a top-down, not bottom-up approach.

An example of a public program designed to foster early and meaningful involvement is the Environmental Justice Collaborative Problem-Solving (EJCPS) Cooperative Agreement, awarded annually by the EPA since 2000. This program is designed to provide resources, including institutional support and funding, for community-based organizations (CBOs), tribal governments, or organizations. The goals of these cooperative agreements and grants are to "help build the capacity of communities with environmental justice concerns and to create self-sustaining, community-based partnerships that will continue to improve local environments in the future" [15]. By placing CBOs and tribes in a central role as principal investigator and project manager, these groups are empowered to develop a community-centered vision and change agenda [16].

NEJAC created a Model Plan for Public Participation which is based on two guiding principles and four critical elements [17]. The guiding principles call for public participation that includes communities, maintains honesty and integrity, and facilitates dialogue as equal partners. The four critical elements include:

1. Preparation: co-sponsors and co-planning are vital for a successful meeting.
2. Participants: a wide variety of stakeholders should be involved in EJ issues, from community and neighborhood groups, government agencies and decision-makers, industry, and a spectrum of nongovernmental organizations and spiritual communities.
3. Logistics: meetings should be accessible; the time/days when meetings are held should reflect the needs of the affected communities; avoid panels and "head tables" to maintain an atmosphere of equal participation.
4. Mechanics: use a professional facilitator; maintain clear goals, but also build in flexibility; develop an action plan; and identify responsible parties.

(A more comprehensive list of suggestions can be found in [17].)

13.2.3 Perception and Risk Assessment

Perception is how people recognize, apprehend, or evaluate their situation based on their life experiences and culture. An easily comprehendible example of this is that a person living in the smallest house on a block may feel poor even if the home is nicely maintained, but if living in the same house in a poor neighborhood he or she may feel quite lucky to have such a nice home. Perception, therefore, is very much about how we feel we are being treated in comparison to others. That is not to say that a violation of one's rights is only "in his/her mind." What it does say is that when a group of people has been discriminated against time and time again, they are likely to feel the sting of a proposed LULU in their neighborhood more acutely. The environmental risk may or not be high. How do we assess that?

Environmental risk is defined as the chance of harmful effects to human health or to ecological systems resulting from exposure to an environmental stressor, where stressors are any physical, chemical, or biological entity that can induce an adverse response. Generally, risk can be evaluated through *risk analysis*, which has primarily a technical focus; *risk management*, which has primarily a policy focus; and *risk appraisal*, which focuses primarily on social aspects. Most readers are familiar with the risk characterizations resulting from risk analysis, sometimes called risk assessment, as these tend to make the headlines in web articles or news stories. An example would be an analysis indicating the increased risk of mortality or cancer from exposure to a particular environmental pollutant. Wilson identified activities (and their causes) that increase one's risk of death by one in a million (0.000001); these varied from smoking 1.4 cigarettes (lung cancer) to flying 6000 miles by jet (cosmic radiation) to eating 100 grilled steaks (cancer from ingesting benzopyrene) [18].

Much of the time, the scientifically derived probability and consequence of undesirable events do not correlate well with the degree of public acceptability associated with that risk. Risk appraisal is the process of identifying, evaluating, and comparing the factors associated with individual and societal response to health and environmental risks. Risk appraisal research methods include *expressed preference studies*, for example, survey methods such as opinion polls to measure public views on environmental risk issues. *Revealed preference studies* involve a more indirect assessment such as examination of historical data to determine public preferences and views.

Factors that influence public response to environmental risk include beliefs, environment, economics, and fairness (BEEF).[1] Initially the mnemonic "BEEF" arose from a popular 1980s Wendy's fast-food chain commercial in which a little old lady asked memorably "Where's the BEEF?" Today the mnemonic is still useful, as the idiom "have a beef with (someone or something)" refers to having an unsettled dispute with someone. A brief description of these factors follows:

- *Beliefs* (individual and societal)
  Includes risk perception factors, environmental attitudes, world views, group norms, political ideology, and cultural beliefs.
- *Environment* (social and physical)
  Includes contextual framing effects, political and cultural history of risk, trust in information sources, type of intensity of risk, and uncertainty of data.
- *Economics* (individual and societal)
  Includes monetary and behavioral cost/benefits appraisal at individual, regional, or national level; endowment effects; willingness to pay versus willingness to accept; and tangible versus environmental values.
- *Fairness* (distributive and procedural)
  Includes equity of risk distribution at individual, regional, or national level; procedural fairness of risk distribution at individual, societal, and national level.

Characteristics of LULUs themselves can also impact the public's or an individual's level of perceived risk and NIMBY response. Some characteristics decrease

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[1] The mnemonic BEEF as used here, and much of the information in this section, derives from a lecture on environmental risk assessment by Brenda Nordenstam, PhD, SUNY College of Environmental Science and Forestry, Syracuse, NY, November 3, 2003, and multiple years thereafter.

Table 13.1 Factors which increase or decrease risk perception: a summary of findings by Rogers, and Slovic and others [19, 20]

Decreases risk perception		Increases risk perception
Voluntary	vs.	Involuntary
Chronic	vs.	Catastrophic
Common	vs.	Dreaded
Injurious	vs.	Fatal
Known	vs.	Unknown
Controllable	vs.	Uncontrollable
Familiar	vs.	New

risk perception, while others may increase perception of risk (Table 13.1). For instance, if a person or community has lived for many years near a waste incinerating facility, that person or community will not be as concerned about risks of mercury poisoning as they might be if the facility were a new one proposed to be built near their neighborhood.

13.3 Hazards to Communities

13.3.1 Pollutants of Concern

Before presenting some case studies of EJ claims and how they were resolved, it is important to consider what the potential hazards are to communities impacted by the siting of undesirable facilities. Many urban pollutants like ozone, NOx, and SOx impact the respiratory system and have contributed to the epidemic of asthma in young children across the United States (Table 13.2). Others that have been identified over the years are dioxin, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), mercury (Hg), and benzene, toluene, xylene (BTX), which can be even more detrimental. The EPA Toxic Release Inventory (TRI) provides citizens with information on what pollutants have been identified in their geographic area and at what industrial or waste sites [22]. The TRI inventory lists 595 chemicals and updates this list as needed [22]. The list includes those chemicals known to cause cancer and other chronic human health effects, those with significant adverse effects on human health, and those with significant adverse effects on the environment. TRI tracks the pollution prevention progress and waste management by facilities of certain toxic chemicals that may pose a threat to human health and the environment. Companies or facilities that have been identified as polluting must report annually how much of each chemical is recycled, combusted for energy recovery, treated for destruction, and disposed of or otherwise released on- and off-site. There are five categories of toxins that because of their persistence in the

Table 13.2 Summary of impacts to human health

Pollutant	Impacts
CO	Reduces O_2 circulation in body, affects concentration and learning ability, aggravates cardiovascular diseases
NO_2	Irritates lungs, increases likelihood of respiratory illnesses like the flu
Tropospheric O_3	Affects lungs and aggravates respiratory problems like asthma
Pb (lead)	Stored in many different parts of the body, mainly affects the nervous system causing learning and behavioral disorders
PANs	Eye irritants
SO_2	Affects the respiratory system, especially children and elderly
PM	Affects the respiratory system, especially those with respiratory problems

Source: Adapted from [21]

PAN peroxyacetyl nitrate, a component of smog. Formed by a combination of sunlight, NOx, and hydrocarbons, all in great abundance in Los Angeles, for instance

Table 13.3 Summary of impacts to leaves of trees from selected pollutants

Pollutant	Impacts	Most sensitive
SO_2	Spots, loss of color, increased susceptibility to pathogens	Middle-aged leaves
O_3	Spots, flecking	Oldest leaves
PANs	Glazing, silvering, bronzing on lower leaf surface	Youngest leaves
NO_2	Irregular white or brown lesions	Middle-aged leaves

Source: Adapted from [21]

environment and their bioaccumulative[2] nature require more stringent reporting. These include dioxin and dioxin-like compounds, hexabromocyclododecane (HBCD—brominated flame retardants), lead (Pb) compounds, mercury (Hg) compounds, and polycyclic aromatic compounds (PACs), of which PAHs are a subgroup. Often the pollutant effects are visible in the leaves of neighborhood trees (Table 13.3) (see Chap. 8 for more discussion of pollutant effects on urban trees.). The metabolism of exposed communities to these chemicals is negatively impacted via the following pathway: illness → school absenteeism/learning disability → educational attainment → unemployment → poverty.

13.4 Analytical Tools

One method of determining whether a community's claim of unfair treatment is valid is to apply geographic information systems technology. Using the most current US census databases and digital maps of census blocks, we can assess the demographic

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[2] Bioaccumulative refers to the presence of a chemical in tissue of living organisms that magnifies as one moves up the food chain. Also the older and larger an organism, the more concentrated is the chemical, i.e., more of the chemical per unit tissue. This may be due to the larger amount of fat in the organism.

profile of that community, primarily race and economic status as measured by the Census metric "the percent below the poverty line." That profile must be compared to the profiles of other neighborhoods in the region to determine if the community is disproportionally impacted. A community that meets the threshold of those criteria is called a *community of concern*. The criteria for qualification vary by state. The threshold for minority status is around 50% in urban areas and about 30% in rural areas, whereas the threshold for poverty varies between 18 and 24%. The general guidelines are outlined in section 2 of the EPA's "Final Guidance For Incorporating Environmental Justice Concerns in EPA's NEPA Compliance Analyses" [23]. To do the analysis, the EPA provides an environmental justice and screening tool [24]. It also provides technical assistance grants (TAGs) to communities located near Superfund sites to assist in data interpretation and evaluation of hazards and exposure [25]. Finally, the EPA Toxic Release Inventory Program, described earlier, provides communities with information on the existing hazards in their communities [15].

13.5 Case Studies

Of the many cases of disproportionate environmental impact that have been identified and addressed since Bullard, we select two cases. The first was the resistance to a municipal waste incinerator in the Brooklyn Navy Yards (New York City, NY) in the 1990s. One of the early EJ cases, it is notable and oft cited because of the number of people involved, the unique multi-ethnic/multiracial coalition of Puerto Ricans and Hasidic Jews, and, notably, because the community organizations were successful in preventing the construction of the incinerator [26]. The second case, albeit a less renowned one, revolves around the siting of a wastewater treatment facility designed to reduce the impacts of combined sewer overflows (CSOs) in Syracuse, NY. It demonstrates that some community-led EJ efforts can fail to prevent LULUs from being built but may contribute to paradigm shifts in public opinion and policy. Soon after this case, Onondaga County, where Syracuse is located, changed its tactics for complying with Clean Water Act violations by shifting from gray to green infrastructure.

13.5.1 Incinerator at Brooklyn Navy Yard

Over the twentieth century, New York City burned approximately 110 million tons of municipal waste in 24 large incinerator facilities, and approximately 17,000 domestic waste combustors in apartment buildings scattered across the 5 boroughs (much of the remainder was buried in the Fresh Kills Landfill on Staten Island, and 6 other landfills deliberately located on salt marshes) [27]. By the 1980s, however, the environmental, health, and financial costs of incineration closed down most of the city's municipal facilities. By 1993 all the large plants had shut down, and regulations had ended the operation of domestic incinerators around the city [28].

A plan to construct a large (55 story, 3000 ton-per-day) waste-to-energy plant at the Brooklyn Navy Yard in the Williamsburg neighborhood persisted through the 1990s despite the trend toward incinerator closures because it offered an alternative to Fresh Kills Landfill, which was also under pressure of imminent closure. The Williamsburg neighborhood was inhabited by two deeply divided ethnic groups, Puerto Rican and Dominican Catholics, and Hasidic Jews. Despite their ethnoreligious differences and history of conflict, the two groups banded together to oppose the construction of the plant [26]. Over several decades community groups and NGOs worked individually and together, in and outside of the courts, in a long and complicated fight based on the premise of environmental justice. Twenty neighborhood organizations formed the Community Alliance for the Environment. Iconic images showed the two groups walking arm in arm in streets. Despite some early setbacks, the neighborhood groups ultimately prevailed, and the plans for the incinerator were scuttled by state legislators in 1996. The last incinerator in New York City, a small medical waste facility, was torn down in 1999, and the Fresh Kills Landfill closed in 2001 [28]. Today a majority of the city's municipal waste is shipped by rail, truck, and barges to landfills and waste-to-energy facilities (incinerators) in Upstate New York, Pennsylvania, New Jersey, and Virginia or recycled [29].

13.5.2 Midland Regional Wastewater Treatment Facility

In this case, community groups in the Midland neighborhood of Syracuse, NY, rallied over a decade in what ultimately would be a failed attempt to prevent a regional sewage treatment facility from being installed in a poor and predominantly African-American neighborhood (Fig. 13.1). The facility, one of several planned across the city, was designed to collect, partially treat, and store stormwater and wastewater to prevent combined sewer overflows (see Chap. 6 discussion of CSOs). The need to build this facility was mandated by an Amended Consent Judgment (ACJ) resulting from a lawsuit brought by the Atlantic States Legal Foundation (an environmental citizens' action group) to clean up Onondaga Lake and its principal tributary, Onondaga Creek, on behalf of the residents of the city under the Federal Clean Water Act. The site had been selected based on consultant engineers' recommendations that it was the low elevation point at which several combined septic/storm lines converged or could be converged. The engineers' design specified the installation of swirlers to remove solids, chlorine treatment, and re-release of treated effluent back into the main trunk line or the creek on high-volume days if the storage capacity was exceeded. Building the facility, however, required relocating 35 families, demolishing their homes, and destroying a highly frequented public park used by local youth to play basketball. The Midland community argued that CSOs could be addressed more safely, aesthetically, and cost-effectively with green infrastructure and underground storage than by chlorine-based technologies with an eyesore aboveground treatment/storage building. They filed a Title VI complaint[3] against the

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[3] Title VI 42 U.S.C. § 2000d et seq. Was enacted as part of the landmark Civil Rights Act of 1964.

Fig. 13.1 Homes bordering Midland neighborhood park boarded up in preparation for construction of a regional sewage treatment facility. (photo courtesy of M. Hall)

county, the NY Department of Environmental Conservation, and the US EPA claiming discrimination. Despite meeting the definition of a community of concern (85% of residents are African-American) and a history of environmental injustices (including legacy pollution from a large industrial park adjacent to their community, the city's school bus distribution center and parking lot, the dry cleaning facility for a large local hospital's linens, and repeated evictions of homeowners for these municipal projects), their complaint failed, and the facility was constructed as planned [30]. One "silver lining" perhaps is that after this decision, Onondaga County chose to pursue "green infrastructure" rather than gray infrastructure in its attempts to meet the spirit and the requirements of the ACJ. The construction of two other regional treatment facilities was cancelled.

13.6 Conclusion

The environmental injustice that exists today is the result of prejudice, intolerance, and historical or ongoing power and wealth imbalances. Disproportionate exposure to environmental risks can be also exacerbated by local environmental conditions and one's geographic location, e.g., proximity to the coast. People's ability to react,

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It prohibits discrimination on the basis of race, color, and national origin in programs and activities receiving federal financial assistance, https://www.justice.gov/crt/fcs/TitleVI-Overview.

adapt, or insulate themselves from environmental harm is a function of their access to resources, their social connectivity, and knowledge. Because environmental injustice lies at the connection between human and natural components of urban systems, one must approach solutions to these issues holistically. Over the past several decades, progress has been made toward achieving environmental justice through grassroots and community organization, changes in policy, and increased collaboration with communities during the decision-making process, but many EJ challenges remain, and new threats, such as contaminants of emerging concern and the impacts of a changing climate, remain.

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Part IV

Designing Solutions to Deal with Impacts of Urbanization: Past, Present, and Future

Chapter 14
Urban Food Systems

Stephen B. Balogh

Abstract This chapter provides an overview of the local and distant impacts of urban food consumption, introduces the concept of food deserts in cities (lack of access to healthy food), and describes efforts to improve the sustainability and resilience of urban food systems to extreme events and supply disruptions.

Keywords Urban · Food systems · Resiliency · Sustainability · Environmental impact · Environmental justice

> Eating is an agricultural act.—Wendell Berry

> Eat food. Not too much. Mostly plants.—Michael Pollan

14.1 Introduction

There are few daily decisions that impact the planet more than the answer to the question, "What will I eat today?" This question is asked by tens of thousands to millions of people in your city, and billions around the world, several times each day. Each meal, whether we realize it or not, connects us to the productive capacity of the earth, as well as its waste-assimilating processes. Our food choices connect us to rural livelihoods, the global transportation system, migrant workers, packers, processors and distributors, and even urban marketing firms.

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The poorest among us may ask, “Can I put *enough* food on the table?” while the impoverished ask, “Can I put *healthy* food on the table?” Urban residents may ask, “Where does my food come from?” The satiated or socially conscious may reflect, “Can I put *environmentally- or animal-friendly* food on the table?” and “How do my food choices impact my community?”

A deep understanding of the food system and our food choices, then, requires a multi- or interdisciplinary systems perspective that considers ecology, economics, as well as philosophy, ethics, social justice, and anthropology. This chapter reviews some of the many challenges to creating sustainable and resilient urban food systems, provides insight into social and environmental justice issues related to food, provides an integrative perspective from which food systems can be analyzed, and, importantly, highlights innovations and solutions being implemented in cities around the world.

14.2 Environmental and Social Impacts of Our Food Choices

Chapter 2, Urban Ecology from a Biophysical and Systems Perspective, provides a history of human endeavors in agriculture and the impacts of those endeavors on the prehistorical and modern world. That history brings us to the twenty-first century, in which a typical American family of three purchases about a metric ton of food per year [1] and one-third of that food is wasted [2]. Food demand originating in cities can be connected to wide-ranging impacts on the environment [3]. Natural lands have been and are still being converted to croplands and pastures. Soils become depleted of nutrients quickly and must be supplemented with fertilizers. The fixation of nitrogen for fertilizers and release of carbon dioxide and methane from crop farming and domesticated animals impact global biogeochemical cycles. Modern farming is increasingly dependent on fossil fuels for mechanical energy, for petrochemical fertilizer and pesticides, and for processing, distribution, and refrigeration. In some cases, the adverse impacts of industrial agriculture are far removed. But for some riverine or coastal cities, the impacts of agriculture compound local degradation, including pollution of adjacent waterbodies.

14.2.1 Land Use Change

Traditionally, as cities grow, natural lands are converted to agricultural lands to grow more food to meet demand. In some cases, this may mean that nearby forest or grassland is converted to farmland, but in today’s globalized society, land use change can take place in faraway places [4]. Population growth in Shanghai, for example, may lead to forest loss in South America or expanded pastureland in the Midwestern United States as those communities supply food across thousands of miles. The loss of natural lands reduces habitat area for native species and may lead to erosion; excess sedimentation of streams, lakes, and estuaries; loss of soil fertility; and greenhouse gas emissions [5]. Newly cleared roads can create a positive feedback loop of new human settlements (this has been particularly true in tropical rainforests of South America and Southeast Asia), which increase demand for agricultural production. Globally, 0.22 hectares of arable land are needed to support the average adult [6]. The area farmed (crops and grazing) per capita can be much higher in developed countries (e.g., 0.37 ha/adult in the United States) due to the demand for protein in the form of meats, cheese, milk, etc. Many countries in the global south or less developed world must contend with much less (0.17 ha/adult), and they tend to eat lower on the food chain.

14.2.2 Impact on Global Biogeochemical Cycles

To meet the growing demand of a growing population, farmers must prevent nutrient loss and the degradation of fertile soils and improve productivity. Natural sources of nitrogen, phosphorus, and potassium soil nutrients are labor-intensive (manure) and limited (phosphate rock or guano). The Haber-Bosch process, developed in the twentieth century to fix nitrogen from the atmosphere into reactive forms (used initially to produce gunpowder), forever changed the biogeochemical cycles of the planet. Worldwide, the Haber-Bosch process now produces nearly 500 million metric tons of reactive nitrogen fertilizer per year from nonreactive nitrogen gas in the atmosphere and consumes 1–2% of the world's energy supply. Fertilizers and selective breeding of cultivars have more than quadrupled the productivity of farmland (corn yields have increased to nearly six times their 1900 value, from 1.6 to 9.5 metric tons/ha) [7], thus reducing the pace of land use change; however, excess fertilizers applied to farmland make their way into streams, rivers, lakes, and oceans. Fertilization with phosphorus causes eutrophication in freshwater streams, rivers, and lakes, while fertilization by nitrogen has similar effects in saline embayments and the open ocean. Eutrophication stimulates growth of micro- and macroalgae, and when those plants die and decay, dissolved oxygen in the water is diminished or depleted, leading to uninhabitable zones and die-offs (see Chap. 9 for a more in-depth discussion of nutrient cycling in our environment). Pesticides and herbicides can impact ecosystems beyond the boundaries of a farm, too. Many birds, fish, amphibians, and insect pollinators are susceptible to these chemicals.

14.2.3 Dependence on Fossil Energy

Food production, transportation, processing, and storage systems use approximately 15–20% of US energy consumption [8]. Human labor and solar energy inputs made up nearly all the energy inputs into early subsistence farming. The domestication of animals allowed animal labor to be substituted for human labor but also required a larger area to be farmed. Further development of agricultural technologies improved the efficiency of farming for people, but the advent of mechanized farm equipment in the early twentieth century led to decreased efficiency across the agricultural system, on a kcal of energy input to kcal of output basis [9]. By the 1970s, some 5–10 kcal of fossil, animal, and human energy were required to produce 1 kcal of edible food. Advancements in irrigation technology have allowed previously marginal land to be put into production but required additional energy consumption requirements. Today, that trend is reversing with marginally improved efficiency in the United States [10].

14.2.4 The Impact of Meat and Animal Product Consumption

A diet containing high amounts of meat is associated with higher greenhouse gas emissions, greater land use change, and greater nutrient pollution in water [11]. In contrast to grains, which are mostly grasses and very productive, yields of meat and animal products are much lower on a per area and per input basis. About 3–30 people can be supported per hectare on grains alone, but much fewer if the crop is first fed to animals. Therefore, in countries with the largest populations, many people eat a primarily vegetarian diet of mostly grains, usually rice, and this is true for low-income populations globally. Energy yields for animal products tend to be 10% or less than an equivalent area of grains. This is because the energy conversion efficiency of plants to animal flesh is only 10–20%. Six units of plant protein must be consumed by livestock for each unit of animal protein produced [12]. However, animals do have the advantage that they can be fed from lower quality, less productive land where it would be expensive or difficult to grow crops [12].

Farmers in the United States raise and care for 100 million beef cattle and calves, between nine and ten million of those are dairy cows. Some 110 million hogs are raised and slaughtered, and over nine billion chickens and turkeys are hatched each year. Ninety billion eggs and some 22 billion gallons of milk were produced on farms in the United States in 2010 [13]. About 100 kg of meat is eaten per American per year. As wealth increases in some countries, for example, China, diets are shifting toward an American-style, high meat consumption diet.

14.2.5 Food and Human Health and Well-being

Food security, or the availability and adequate access at all times to sufficient, safe, nutritious food, is directly connected to human health and well-being. A lack of food security is associated with increased frequency of chronic diseases and poor performance at school and at work [14]. Social barriers and economic status limit food choices. Some four million Americans, predominantly in cities, live in food deserts. Food deserts are typically low-income areas with limited access to healthy and affordable food, such as communities where more than a third of the population is greater than a mile from the nearest grocery store.

14.2.6 Food and Sociopolitical Impacts

Food supply, demand, and availability can have sociopolitical impacts that span nations and the world. In the United States, renewable Fuel Standards provide an obvious example of the nexus between food, energy, and policy. Thirty-eight percent of the corn grown in the United States was used to produce ethanol in the 2017/2018 market year [15]. Most of this ethanol was consumed in vehicles within US metropolitan areas. Other clear links between food, energy, water, and policy in the United States include the western water rights issues which link agricultural production, electricity generation, drinking water supply, and environmental conditions. The Colorado River, for example, provides water to 40 million people across 7 states, is used to irrigate 5.5 million acres of land, and provides some 4.2 GW of electricity generating capacity [16]. These competing ends often lead to contentious debates about the "ownership" of water. Globally, export crop production, e.g., coffee, can be a boon for farmers but leaves them vulnerable to changing global markets for income. Many coffee farmers must go into debt to weather lean years and to purchase agricultural chemicals [17]. Increases in global food prices directly impact import-dependent countries. Some postulate that rising food and commodity prices in the 2000s contributed to the Arab Spring and other uprisings in cities in Northern Africa and the Middle East [18]. Increasing globalization of markets and of diet has led to a loss of cultural heterogeneity and social bonds. Fast food, especially American fast food, is ubiquitous.

14.3 Challenges to Creating a Sustainable and Resilient Urban Food System

Cities are consumptive entities. Ancient cities were surrounded by productive and fertile areas such as river valleys, estuaries, and coasts. Later cities arose at the confluence of trade routes, or in areas containing an important resource, taking advantage of the fact that food could be brought in from distant productive areas. Today, formerly productive areas near urban centers have been covered over with impervious surfaces or degraded due to overexploitation or pollution. Most modern cities, perhaps except for a select few like Paris, benefit from but are highly dependent on a distant resource-shed and global food markets. The average distance that food travels to a supermarket in the central United States is around 1500 miles for domestic food and 2200 miles for international imports [19]. The benefit of this more integrated and global supply chain is a system that is more resilient to disruptions, meaning a local crop failure does not lead directly to famine. Additionally, the most fertile lands in a nation can be used in lieu of locally less productive areas. One trade-off that results, however, is that this system contributes to increasing atmospheric carbon levels as food must be transported a long way via ships, trucks, and rail.

14.3.1 Urban Food Production

The solution prescribed to combat the lack of fresh and local food in urban food deserts is to increase urban food production; however, there are many challenges to producing more food in cities, among them a lack of space, soil, and know-how. Urban space is scarce and land uses tend to be exclusionary. Urban agriculture has difficulty competing against commercial, industrial, or residential uses in areas with high property values and taxes (Fig. 14.1). Most cities do have

Fig. 14.1 Chicago, IL. Some new crops being started, protected by shade cloth barriers to the west. Note the new construction in the background. This area used to be all public housing. The high-rise "warehouses of the poor" were torn down and are being replaced with mix of market-rate and low-income housing (also called mixed income housing). The 1.5 acre parcel that City Farm sits on is owned by the City of Chicago and provided, rent-free, to this nonprofit initiative. The property is valued at $8 million, however, so it's anyone's guess as to when the city decides to terminate the agreement and City Farm must move again. Photo credit: Linda N. ©2008 https://commons.wikimedia.org/wiki/File:New_crops-Chicago_urban_farm.jpg

abandoned or vacant properties that could be used to grow food; however, many of these sites have poorly compacted soils with legacy pollution (typically lead or other heavy metals) or may be covered with impervious surfaces [20]. Additionally, there may be human capital deficits, meaning a lack of knowledge on how to grow a crop. Food and energy surpluses have allowed a growing majority of adults to pursue nonagricultural careers (in 1870 half the US population were employed in agriculture [21] compared with less than 2% today [22]), meaning city dwellers may be several generations removed from the last person in their family to tend a garden.

14.3.2 Food Processing and Distribution Challenges

Beyond difficulties in producing food, there are issues related to processing and distributing locally grown or produced food products. Commercially grown food must be transported to a processing and distribution center to be sold in retail stores. These processing sites may or may not be in city centers, meaning that animal or food crops would need to be transported out of the city in which they were grown to be processed and then shipped back to that neighborhood before they can be sold. Prepared foods must be processed in commercial kitchens which undergo rigorous, regular food safety inspections. Local entrepreneurs may lack access to these kitchens or have insufficient volume necessary to afford their use. There are other socioeconomic barriers to local food access. While the federal government allows for Supplemental Nutrition Assistance Program dollars to be spent at farmer's markets, the ease of doing so varies from state to state. Transportation options may be limited, and some neighborhoods will be more distant from markets than others.

Despite these difficulties in producing and processing food in cities, some have persevered and have created successful urban farms and gardens which provide either a niche product (microgreens in Brooklyn), an engaged and enthusiastic community (Will Allen's "growing power" in inner city Milwaukee) or personal triumphs and healthy supplements to their family's diet: backyard chickens in Denver, a roof garden in Brooklyn, schoolyard vegetables in Long Beach, California. Moving further out along the gradient between urban and rural, a small but growing number of suburban homeowners are trying their hand at gardening. Once common in American backyards during World War II ("Victory Gardens") and still common among many communities worldwide, about 1/3 of American households have a garden today. Community gardens and shared plots can be found in most cities, providing access to arable land and a knowledge base for those lacking in space, time, or experience (Fig. 14.2). For those unable or unwilling to grow their own food, farmer's markets and community-supported agriculture (CSA) provide important direct links between local farms and urban and suburban customers. In the latter, customers can buy a "share" of a farm's production for the year. Weekly deliveries during the growing season provide CSA participants with fresh, local

Fig. 14.2 Dining in the Davie Community Garden, Vancouver, BC, Canada. Photo credit: Geoff Peters ©2010 https://commons.wikimedia.org/wiki/File:2010_Davie_Street_community_garden_Vancouver_BC_Canada_5045979145.jpg

food, but deliveries are limited to fruit and vegetables that are ripe and do carry some risk of loss due to infestation or drought.

14.3.3 *Food Waste and Linear Nutrient Flows*

An additional barrier to urban food sustainability and resiliency is the one-way flow of nutrients from farms to dinner plates to urban waste streams. The nitrogen, phosphorus, and other nutrients which nourish our and our pets' bodies end up in solid waste streams, conveyed by sewers to a wastewater treatment plant (that typically doesn't remove nutrients) or enter the groundwater via septic systems and cesspools. Unlike for nitrogen, there is no Haber process available to us to produce phosphorus. Much of the phosphorus flows are linear and end up diluted in water bodies or the ocean. This vital agricultural nutrient must be mined from concentrated source rock found in only a handful of countries, collected from guano, or recycled from animal manures. Karl Marx, an early proponent for closing material loops, observed the transfer of soil fertility from farms to cities via the deposit of manure from beasts of burden and described this as the "metabolic rift."

The composting of food and yard waste adds a material reuse loop and can reduce fertilizer demand in cities and suburbs. Some conscientious urban citizens compost their food waste in backyard compost bins, and some progressive cities like San Francisco, California, Portland, Oregon, Cambridge, and Massachusetts provide curbside pickup of compostable waste. In Cambridge, municipal compost is turned into a slurry and anaerobically digested. The methane it produces is used to heat homes and make electricity. In both municipal and household composting, the rich organic solids can be used as fertilizer. Overall though, cities have a long way to go to close nutrient loops. Compostable food waste makes up nearly 22% of the municipal solid waste destined for landfills or incinerators, some 51 million metric tons per year [23].

14.4 Urban Food Resilience

Ecological resilience has been defined as the ability of a system to resist or recover from change and disturbance while still maintaining the relationships between its components [24]. Similarly, the concept has been applied to food systems. Usually food resilience refers to the ability of agricultural production to keep up with growing populations, maintaining food availability in the face of climate change or decreased fossil fuel production, and the availability of safe and sufficient food in cities despite disruptions to supply [25]. This chapter focuses on the latter, but the impacts of population growth, climate change, and peak oil on food availability are subjects worth learning more about (see suggested readings at the end of the chapter).

Resiliency in an urban food distribution system can at times be undermined by just-in-time inventory management systems. These have the primary objective of eliminating waste from manufacturing and delivery processes by reducing the need for storage space and costs while increasing energy and material efficiency [26]. Input materials arrive just as they are needed for manufacturing, assembly, distribution, or sales—a concept that began in the manufacturing sector and has made its way to the food distribution system. Supermarket chains have become adept at managing inventory stocks and the daily flows which replenish them. For the most part, shoppers are greeted with full shelves and adequate stocks, even during busy holiday shopping seasons. The just-in-time inventory management and complacency on the part of consumers reveals its vulnerability, however, during storms, natural disasters like hurricanes and earthquakes, or other emergency situations. During these unexpected events, “runs” on the food store lead to bare bread aisles, empty milk cases, and depleted stocks. Usually these shortages are short-lived and within a day or two, stores have been replenished with deliveries. From the free-market economists’ perspective, this relatively short period of disruption is evidence of the benefits of a globalized food system that has the capacity for redirecting stores of food to places in need. Longer-term disasters and energy supply disruptions like during the aftermath of Hurricane Maria in Puerto Rico expose deeper levels of vulnerability in the supplier-consumer system to food disruptions. Meager community and municipal stocks are quickly depleted and supply chains are disrupted. Novel supply systems must be developed and implemented.

Government readiness campaigns (e.g., www.ready.gov) advise that citizens store enough drinking water (1 gallon per person per day) and at least a 3-day supply of food in the home. Some religious practices require that members keep reserves of food and other staples. The Church of Jesus Christ of the Latter-Day Saints (Mormons), for example, suggests that members store at least 3 months and up to a year's worth of food for one's family. Other means of increasing one's food resilience at the household level include supporting farmers who sell their food directly to the public, learning how to grow and can or store food, and learning how to prepare meals from scratch, including how to substitute for missing ingredients. Community food pantries also provide redundancy when personal or natural disasters strike.

14.5 Using a Systems Approach to Examine Urban Food Production and Distribution

As we've laid out in previous chapters, an appreciation for system complexity and the creation of conceptual or numerical models to explore it can help natural and social scientists and their practitioner counterparts understand the potential impacts of decisions. Since our food choices are embedded in a larger social-ecological system, a broad consideration of system components, interactions, and perspectives can be useful to cut through superficial claims of "greenness" or sustainability.

A social-ecological systems approach can help identify trade-offs in our food choices, knowledge or distribution gaps in the food system, and underlying drivers and pressures on environmental and human health. For example, let's look at a common apple. Urban residents might need to decide between apples that are organic/conventional, local/distant, and inexpensive/expensive. Underlying these decisions are values derived from formal education, mass media, marketing, social norms, spiritual or religious beliefs, and a lifetime of prior decisions. The ideal choice for some—an inexpensive, local, organic apple—might not exist. So instead, some may choose an organic apple imported from Peru, while others might prefer a conventionally grown apple from an orchard on the outskirts of the city. Others may look for the best looking, lowest cost fruit. The only apple option for those living in a food desert might be a jar of applesauce, which comes with added sugars.

Each of these choices, or non-choices, as the case may be, results from historical economic and cultural drivers. Food deserts might be traced back to racially or ethnically motivated decisions, such as those made by bankers during the pre-WWII era (see the comments on "redlining" in Chap. 13). The decision to stock local or imported apples might not be made by a store manager, but instead by a purchasing agent at a distant national office of the supermarket chain, driven largely by shareholder interests. Other influences, like news stories, articles shared on social media, or marketing campaigns may consciously or unconsciously alter our behavior.

When aggregated to the level of the city, our individual decisions have impacts on the economy, the state of our environment, and public health. The lack of healthy food options can lead to chronic illnesses like diabetes or heart disease, or poor performance in schools [27, 28]. Conventionally farmed vegetables may expose consumers, workers, and organisms in natural systems to pesticides, herbicides, and excess nutrients. There are even perverse trade-offs arising from socially or ecologically conscientious decisions, such as the decision to support local farmers by shopping at the farmer's market. While this option may be more beneficial for economic health in the community, it may lead to greater air pollution and greenhouse gas emissions on a per-unit basis. Box trucks transporting food from local farms to farmer's markets are less efficient because they tend to arrive partially filled and head back to the farm empty [29], while other large tractor trailers carry full loads in either direction between distribution points in mainstream agriculture. Methods like life-cycle analysis (LCA) can help quantify the environmental impacts of our food choices. For example, Pelletier et al. [30] performed a quantitative comparison of feedlot and pastured beef production systems in the Midwestern United States. They found that contrary to conventional wisdom, in some cases feedlot systems can have lower life cycle energy consumption and greenhouse gas emissions than pastures in the system that were actively managed with fertilizers and tractors [30]. Going beyond LCA, a broader social-ecological perspective can help quantify or qualify social and economic impacts and link decisions to health and well-being outcomes. For example, Hall and others compared urban gardens to other strategies for developing available space in cities from a social-ecological perspective [31].

14.6 Other Proposed Solutions

Technology has been applied to address many urban problems, often with great success, e.g., communication networks, subway systems, sewers and water treatment, district heating, etc. Technical fixes have been proposed for urban food sustainability and resiliency, too. These range from high-tech robot-tended skyscraper farms (see, e.g., Fig. 14.3) to low-tech community run hydroponic/aquaponic fish and crop production systems. Both systems include nutrient recycling, eliminate exposure to contaminated soils, and bring production close to the consumer, which limits transportation energy consumption and pollution. Community-supported aquaponic systems limit investments in technology to a series of pumps, lights, timers, and sensors and are capable of producing fish protein alongside their crops. Skyscraper farms purport to eliminate the need for pesticides and herbicides by sealing off the growing environment and allow the application of nutrients to be fine-tuned, increasing the efficiency of fertilizer use and preventing eutrophication of urban waterbodies. There may be additional social benefits in the form of revenue, jobs, and enhanced human capital through educational opportunities. These technological fixes, however, face challenges to their widespread introduction and use.

Fig. 14.3 A hydroponic (aquaponic) vertical farm houses hundreds of ZipGrow Towers to grow crops for a Minnesota community. Photo credit: Bright Agrotech ©2014 https://commons.wikimedia.org/wiki/File:Hydroponic_vertical_farm.jpg

Can you use a systems approach to sketch out a diagram of the inputs and outputs of skyscraper farms and aquaponic systems? What challenges can you identify? Can you identify additional benefits? What might make either of them more "sustainable"? Try thinking about composting, backyard gardens, and other solutions mentioned above in the same way. Apply the same critiques. Use some of the information you've learned in other chapters. What co-benefits or challenges can you identify? What other solutions to increasing urban food sustainability and resiliency can you identify?

14.7 Conclusions

Designing sustainable and resilient food systems in cities is important to address food insecurity, environmental and social justice, and the broader environmental and social impacts of our food system. But the challenge is complex. This chapter provides an overview of the difficulties and opportunities associated with increasing food production, creating local distributions systems, reducing food deserts, and empowering citizens. For a deeper dive into these issues, I provide a list of additional books below.

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Chapter 15
Urban Design Toward More Holistic Systems: Improving Discipline Integration and Sustainability Evaluation

Stewart A. W. Diemont and Timothy R. Toland

Abstract Designing the urban ecosystem for sustainability is obviously a complex process. How stakeholders engage in this process and the role that multiple disciplines play in design can help determine project sustainability. Design charettes are a way to ensure that the needs and considerations of the community and the perspectives of professionals are fully integrated. How we define and measure sustainability can guide design requirements. A holistic metric, such as emergy evaluation, could lead to clearer articulation of site and regional relationships across spatial and temporal scales and of the role that nature plays in the urban ecosystem.

Keywords Charette · Sustainability · Multidisciplinary · Site design · Stakeholders · Emergy

15.1 Introduction

Cities are continually in flux, with ongoing cycles of new construction, deterioration, decay, and redevelopment. Although large regional-scale planning opportunities are important to consider for urban ecology, most physical interventions in the urban landscape occur at the site level (see Fig. 15.1). Here "site" can be defined as an area of land ranging from a few thousand square feet (square meters) to several thousand acres (hectares). Site design differs from planning in that work occurs at smaller scales and at increasing levels of detail [1].

Development at the site level generally occurs via the economic, social, and programmatic goals of an owner, developer, and/or municipality. This can be achieved in an ad hoc fashion by individual landowners where impacts to the environment are dealt with on-site, typically addressing required regulatory constraints. This incremental

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Fig. 15.1 Site development: site project along a river that involves a significant number of earthwork and construction activities by heavy equipment. The site underwent extensive shaping to get it to fit the final design. Extensive environmental protections would be required in a project such as this. (Source: Tim Toland)

approach to development makes it difficult to achieve demonstrable improvements to regional ecological health and oftentimes leads to ecosystem (and social) fragmentation (see Fig. 15.2). With this approach, ecosystem services are often compromised. Animal migration, native plant community dynamics, and ecosystem functions such as water cycling and nutrient processing are most effective when considered and designed for at the larger local and regional landscape levels.

The most progressive communities, those that seek to balance the issues of economy and ecology, have established direct links between larger-scale planning issues, environmental system dynamics, and smaller-scale site development processes. This is often achieved through integrated comprehensive planning documents and site development guidelines that recognize the community (both built and natural) as a connected network. These typically will include minimum performance criteria, standards for design, review of site impacts on other systems, and enforcement policies.

Even without these guidelines, the professionals responsible for facilitating development (e.g., landscape architects, architects, engineers, etc.) have the potential to responsibly develop sites by utilizing an interdisciplinary approach. With interdisciplinary design, each discipline works in close collaboration with others to develop holistic, integrated responses to design problems. This approach is critical

Fig. 15.2 Tree preservation areas are typically a component of site development and in some cases contribute to open space and stipulated tree coverage requirements. However, they are usually just fragments of a once larger ecosystem and that, combined with the stresses of construction activity, can severely compromise plant health and sustainability. (Source: Tim Toland)

due to the increasing complexity of site design and environmental issues where no one discipline can address the social and environmental issues alone.

This chapter will discuss a holistic, systems approach to design that considers how each discipline involved in the project interacts with others. Readers will be introduced to the range of theories, issues, problems, dichotomies, and opportunities presented by the interdisciplinary practice of sustainable design and development. Quantitative and qualitative sources for informing design decisions will also be discussed. Current metrics for site-based sustainable design will be discussed and critically evaluated, with discussions on how to exceed these standards with system-oriented evaluations in addition to more common point-based evaluations to improve overall sustainability.

15.2 Background

The issues of contemporary society are complex. Contemporary design, particularly sustainable design, must factor in social, economic, and environmental goals [2]. As has been discussed throughout this book, a broad range of issues impact ecosystems.

These impacts cover numerous geographic areas and affect both local and larger regional systems. While ecological impacts are considered to be large-scale or global problems, projects on small sites and neighborhoods can generate impacts that affect larger systems [3]. Examples include the urban heat island effect exacerbated by asphalt paving and dark roofs, leading to an increased reliance on energy for cooling and increased need for electrical energy due to use of digital technologies, resulting in increased emissions from power plants (see Chaps. 7 & 8). The decision to use asphalt or dark materials is made by designers working at the site level, providing recommendations to clients and directing contractors on the materials to use for project implementation. Designers also make decisions for changes at the site level that call for the installation of infrastructure (e.g., utilities, buildings, landscaping, etc.). In the process of construction, large-scale earthwork in the form of clearing and grading can significantly alter the site and impact ecosystem functions.

Many building products and processes are chosen based on proven reliability (which will reduce liability to a designer), cost-effectiveness, and availability. With some additional consideration, designers do have the opportunity to incorporate innovative materials and other elements that can mitigate environmental impacts and improve regional ecosystem health. Green infrastructure components that manage stormwater on-site, light-colored paving materials that minimize the urban heat island effect, and habitat creation as a component of open space requirements are some examples of how ecologically sensitive elements can be included in a site project. Many of these approaches are beginning to reach a point of maturity where their integration in projects is becoming more accepted due to reliable performance over several years. This trend is expected to continue as ongoing materials research is providing new products to address environmental impacts at the site level.

Project teams that make these decisions while addressing site design are typically assemblages of several different professional disciplines. The development of professional organizations due to increasing specialization and complexity of systems during the Industrial Age [4], and the regulating of design activities through the development of licensure to maintain public health, safety, and welfare, has resulted in the prescribed differentiation of professional specialties. Architects, landscape architects, and civil, mechanical, environmental, and other types of engineers each have their activities regulated by licensing agencies (typically state education boards) and as such have specific tasks which they are and are not authorized to perform.

Additionally, given the interrelated scales at which environmental systems function, the complexity of their interactions, and the breadth of system components, it is difficult for any one profession to fully engage these problems independently. As projects today often seek to find a compromise between social, economic, and environmental goals, interdisciplinary collaboration becomes essential to ensure all factors are considered [2, 5]. The disciplines noted above will each be able to look at these factors and understand them within the context of their discipline and be able to work with other disciplines toward some resolution of professional differences. This interdisciplinary process is also useful to help build the capacity of those involved in the project (e.g., designers, owners, stakeholders, etc.) to engage each other, the public, and the problem more appropriately [6].

The process of developing a site typically involves a client contacting a lead consultant. The lead consultant can be a landscape architect, architect, or engineer, among other disciplines, depending on the project type and relationship to the client. The client can be a property owner or agent acting on behalf of a property owner. These can be private owners, corporations, or governmental agencies with the rights and interest to develop a property. Clients generally establish the design program, which includes the required elements and foundational ideas that guide the project and direct the consultant team toward an outcome. The design program can be specific and somewhat rigid or can be more open-ended and informed by the activities of the consultant team (see Fig. 15.3).

To fully and appropriately address the complex systems involved, the lead designer typically assembles a team of sub-consultants to assist in the project. These sub-consultants represent an array of specialties (e.g., hydraulic engineers, ecologists, wetland consultants, etc.) that are assembled as needed given the scope of the project. The mix of disciplines will vary with each project, and the way a project team is organized and the interactions between the disciplines will affect the final outcome of the design. The ability to work digitally using GIS (geographic information systems) and CAD (computer-aided design) software then helps to facilitate the planning to site design to construction sequence [1].

The design and development of the site will also be informed by regulatory guidelines. Many municipalities have developed zoning and design guidelines that dictate how a site can be developed. Though they vary widely in content, these can include spatial standards for infrastructure elements, massing and density guidelines, buffer requirements, vegetation preservation, and open space requirements. Additionally, local, state, and federal guidelines for stormwater management, wetland and stream protection, brownfield redevelopment, and other systems can either limit types and extent of disturbance on a site or require specific structures and processes to be implemented during a project to mitigate for environmental impacts.

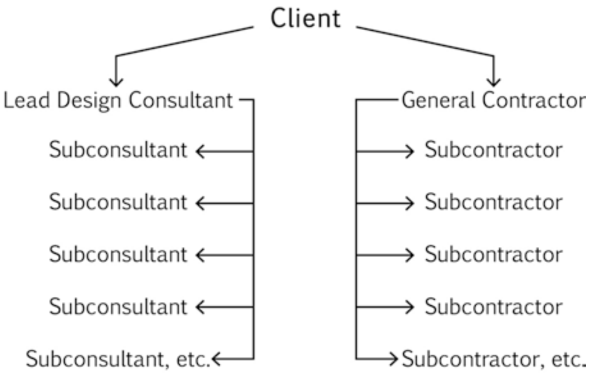

Fig. 15.3 Traditional site development team organization reflecting a top-down structure and a separation between the design process and the construction process. It is common for the designers to be contractually independent from the contractors. (Source: Tim Toland)

The regulatory review process seeks to prevent or mitigate impacts to sensitive systems through the use of erosion control devices, green infrastructure, and other best management practices (BMPs). When disturbance of sensitive environmental systems is unavoidable, regulators may also mandate remediation strategies. These are dependent on the type of system, its quality, and ecological value. Examples include wetland mitigation (e.g., establishing a rate of replacement for each acre disturbed), establishment of buffers along sensitive natural systems such as streams, replanting strategies, or management guidelines.

All of this then is influenced by the physical realities of the site. Each site is a complex association of topography, vegetation, water, soils, and other elements that have typically been impacted by natural and sociocultural influences over the course of time. While contemporary machinery and technology provide for the potential to completely convert a site to most any use, economic and physical realities typically dictate how a site is developed (see Fig. 15.4). Most designers will perform a thorough site inventory and analysis prior to design, trying to garner a better understanding of the site characteristics. This, in conjunction with surveys and geotechnical evaluation, will allow designers to avoid potentially sensitive areas (e.g., wetlands, vernal pools, rock outcroppings, etc.) and take advantage of more appropriate development areas.

Fig. 15.4 Extensive site modification is possible by using heavy machinery. Here part of a hillside and associated vegetation was removed to make room for a new building. The slope was ultimately stabilized with a large retaining wall complex. (Source: Tim Toland)

During the construction process, there is the potential for significant environmental impacts. Exposed soil is prone to erosion, equipment and vehicle use expends significant energy and generates emissions, and unused material can end up in landfills. Soils also can be severely compacted. To mitigate these impacts, the contractor needs to be made an integral part of the design team, as they will be responsible not only for implementation of the design but also for meeting erosion control, pollution control, and waste stream goals.

After construction and occupancy, a site will then have ongoing operations and maintenance activities. These activities have associated costs and potential environmental impacts. The extent of these costs and impacts is often a direct product of how the site was developed and the materials and structures chosen. Stormwater runoff, energy expenditures for heating and cooling, maintenance activities such as cleaning and turfgrass, planting, and structure maintenance can add up over the lifespan of a project site and can oftentimes be significantly more than the impacts caused by construction itself [7]. As discussed previously, there are several competing considerations for the final selection of a material or structure, but if considered during the design process, ongoing costs and environmental impacts can be mitigated through selection of materials, structures, and products that have reduced maintenance requirements or by design address environmental impacts (e.g., stormwater runoff).

15.3 The Collaborative Design Process

Even though a project team is assembled to address the specific issues at hand in a project, the idiosyncratic nature of each discipline creates differing points of emphasis and approaches to the design process (see Fig. 15.5). A hydraulic engineer may

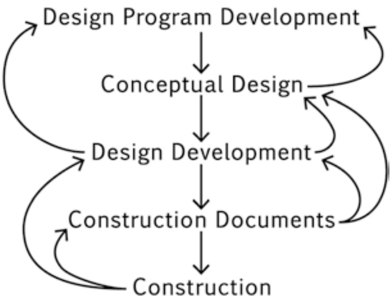

Fig. 15.5 Site development process: site design and development typically involves multiple steps from design program development to construction. While idealized as a linear process, there are frequently factors that require going back and reevaluating earlier decisions. Budget issues, obstacles discovered during the construction process, procurement and availability issues, and other factors can require the design team to go back and redesign aspects of a project, even after construction has started. (Source: Tim Toland)

emphasize the water regime and give secondary consideration to the plant and animal components of a functioning wetland. An ecologist, however, might place greater weight on the plant and animal components. A landscape architect on the same project may emphasize aesthetics, recreational opportunities, and the relationship of the project to adjacent landowners. Building architects may emphasize building systems over site functions. Other disciplines will have their own viewpoints. As site projects rest at the interface between natural and built environments, each point of emphasis is necessary for a project.

Each discipline can develop a solution to a design program individually, but the result typically would be narrow in scope. This narrow focus creates secondary problems in that while one problem is being solved, other important issues may be created. Examples of this include post-World War II highway system development that addressed transportation problems but created social, cultural, and environmental issues in cities like Syracuse, NY, and St. Louis, MO, in the United States [3]. In these cities neighborhoods were cleared to provide a suitable right of way, severing once intact communities, rerouting streams, and resulting in the decline of downtown residential neighborhoods in favor of suburban sprawl. In this situation the transportation issue should have been coupled with a myriad of other planning issues to create more holistic responses. Much of the work of current urban theorists is trying to undo these past mistakes (see Chaps. 1 & 13 for other such examples).

The relationships between the sub-consultants can be complex as each discipline brings their point of emphasis as well as design philosophies and approaches to the project. They also bring specialized terminology and languages that can impede the collaborative process. A lack of a common knowledge base can be an impediment to clear communication [8]. To resolve this, each team member needs to work to understand the idiosyncrasies and language of their colleagues in order to have meaningful dialogue during a project and to develop a common understanding of the systems, opportunities, and constraints presented by the site.

It is up to the lead consultant to manage the various perspectives involved and to coordinate all efforts toward a unified outcome. How the consultants interact with each other and contribute to the end result is a matter of team dynamics, budget, project structure, client direction, and the proclivity of the lead consultant to foster a collaborative process. The assemblage of the various professions will lead to, at the very least, a multidisciplinary outcome.

In multidisciplinary design, the cooperation between the professions will be mutually supportive toward the development of the final design, but the work will not necessarily be interactive [9]. In multidisciplinary design each profession is assigned a specific task necessary for the completion of the project [10]. Coordination typically occurs via meetings and file exchange (e.g., CAD drawings). Periodic meetings typically provide an opportunity for resolution of conflicts between the various elements each profession is managing. An example would be the coordination and refinement of the location of stormwater sewer lines (as determined by civil engineers) with parking lot layout (as determined by landscape architects), in coordination with building drainage (as determined by architects). The solutions proposed by each profession along with the regulatory mandates each must follow are negotiated to some common resolution. In this situation, the lead designer typically will make final determinations and dictate actions, design configuration, etc.

While the multidisciplinary approach described above is a common means of production, it can be inefficient in terms of time and money. Regularly scheduled meetings are required, which are costly and time intensive, particularly if travel is involved. Additionally, should a major conflict arise, its resolution may be delayed until a mutually conducive time to meet is scheduled. This can delay production until decisions are made. In the event a decision to accommodate one profession supersedes that of another profession, changes or revisions to existing design work may be required, again costing time and design fees. Poor communication between team members may create duplications of effort or lead to inappropriate decisions, for example, a mechanical engineer providing oversized air-handling systems for buildings due to poor communication of building size and solar gain aspects by the architect [4].

The give and take nature of design makes some of this unavoidable. But a more effective means of keeping all the professions advancing concurrently is through interdisciplinary, transdisciplinary, or collaborative design. Though Musacchio et al. [8] discuss the differences with these terms, for the purposes of this text, they are generally considered synonymous in that the intent is to seek a more collaborative process between disciplines. With interdisciplinary design, the various representatives of the professions interactively work together throughout the project, and the processes, approaches, and potentially even the mind-set of each discipline are affected and molded by interaction with differing viewpoints. Interdisciplinary design requires a recognition and understanding of the viewpoints and approaches of other disciplines and a willingness to be flexible and mutually accommodating of those differing viewpoints (see Fig. 15.6). By incorporating the viewpoints and

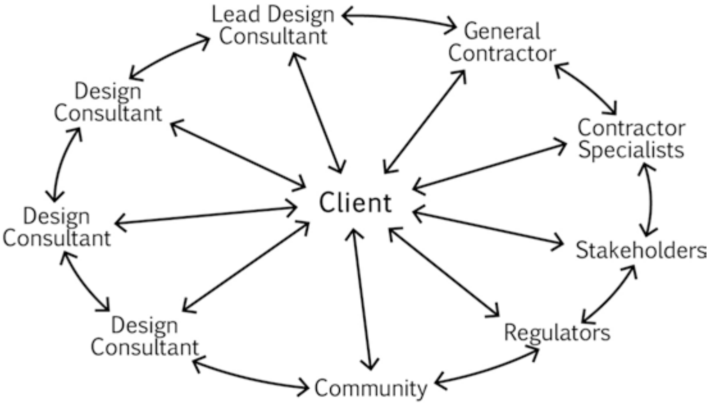

Fig. 15.6 Collaborative design process that shows how project teams can be organized to provide improved lines of communication between all participants. Here all consultants and stakeholders are involved in the design process and have an equal voice in the project. All participants ultimately refer back to the client. (Source: Tim Toland)

Fig. 15.7 Design charrette for a transportation planning project. Here representatives from landscape architecture, transportation and civil engineering, and the municipality work around a base map to propose solutions. (Source: Tim Toland)

knowledge base of allied disciplines into one's own process, a designer can begin to develop more holistic alternatives that incorporate the unique aspects of all disciplines.

The main vehicle for which interdisciplinary design occurs is the charrette. A charrette is an intensive design effort where representatives of each discipline work together side by side to develop alternatives (see Fig. 15.7). Charrettes have their history in the art schools of the eighteenth century. With the use of community engagement practices becoming more prevalent, charrettes have become the preferred approach for getting citizens, stakeholders, and other representatives with an interest in the project to work with the design team to become integral participants of a project [3].

The key to a successful charrette is a clear vision from the client as to their desired design program and well-articulated goals and objectives to be achieved. How broadly the problem(s) is defined and, therefore, how well the key contributors to a broad solution are represented are also important. It is critical to have the appropriate professionals, citizens, stakeholders, etc. involved to be able to holistically and immediately address the issues at hand [3]. Here again, one profession is typically chosen by the client to act as the lead, and it is the responsibility of that group of professionals to establish the targets for the charrette (e.g., products, time frame for production, etc.). Within the charrette process, opportunities for direct feedback

Fig. 15.8 Conceptual design for a park and streetscape project being presented during an interim charrette presentation. (Source: Tim Toland)

from all participants must be built-in to ensure that the team members are working toward the required programmatic, regulatory, and client needs (see Fig. 15.8).

Charrettes can last from a few hours to several days, depending on the size and complexity of the project. Since each profession in the design process is represented, their needs, concerns, and ideas can be immediately explored and incorporated into the discussion. Potential issues can be dealt with before too much time and energy have been expended by any one profession and mutually satisfactory resolutions adopted earlier [3]. The discussion and debate among the professions can also lead to better and more creative solutions. What may seem like a set constraint for one profession may be removed by another, allowing for both to advance an idea. An example would be road locations along a stream corridor restoration project. To the hydraulic engineer, existing roads may be set barriers to reestablishing creek meanders. A landscape architect may be able to advise that roads can be relocated and propose new routes, opening up land for re-patterning the creek (see Fig. 15.9).

Within the charrette process, the role of each participant, including nonprofessionals, is that of contributor. It is at this point that all ideas should be welcomed, and all issues identified and addressed. Successful charrettes begin without preconceived solutions. The solutions evolve out of the exploration, discussion, and debate that ensue throughout the process. As the opinions of all participants are valued and the individuals are typically recruited due to their buy-in to the program and outcomes, differences of opinion can generally be resolved by consensus, by the team leader, or in the development of multiple options that can be compared at a later

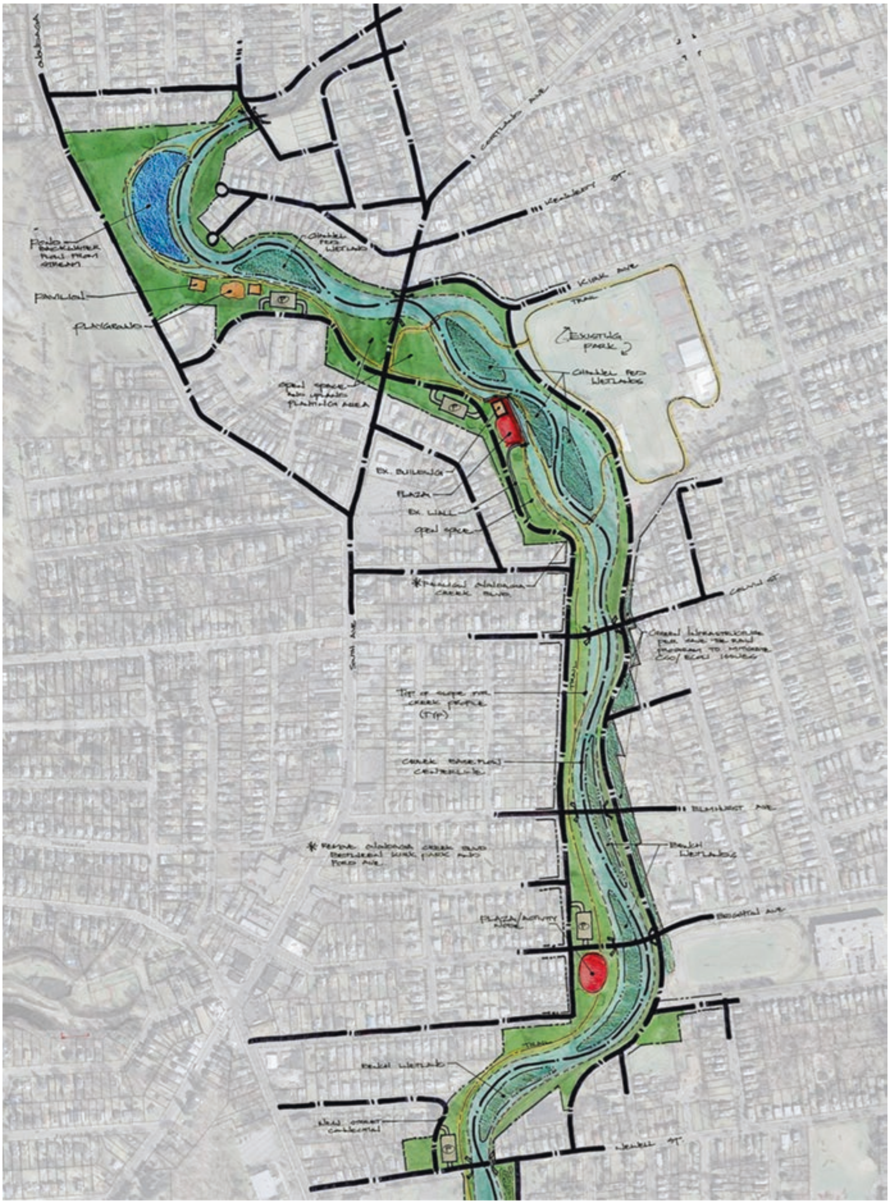

Fig. 15.9 A typical charrette product produced by hand drawings on trace paper over a base image. With this project landscape architects, hydraulic engineers and ecologists proposed the re-patterning of a channelized stream corridor by removing redundant roads and taking advantage of existing open lawn areas. (Source: Tim Toland)

date. Working with others in such an environment requires an understanding of the vocabulary and predilections of the other as well as patience, empathy, mutual respect, and understanding [1, 3]. The products of a charrette will be much stronger having been vetted throughout by each participant.

The charrette process typically results in a vision and conceptual design that addresses the needs and concerns of the client, design program, professions, and community members [3]. From this common starting point, these conceptual ideas can then be taken to advanced levels of design, with each discipline addressing the issues germane to its profession. Having already addressed and concurred on the initial concerns and issues allows each group to move forward more efficiently in detailed design after the charrette.

The open spirit of give and take should be maintained throughout the design phase of a project. Keeping all team members involved in open and ongoing discussions with clear objectives and good communication can help lead to better built works. There may be multiple charrettes or similarly formatted meetings throughout the project [4].

15.4 Stakeholder Involvement

When working in any community, there is a significant amount of local and indigenous knowledge that can be of great importance to the development of proposed design solutions. This knowledge can include things such as the site's history, the individuals and activities that have impacted its use, current activities occurring on the site, and most importantly how the site might be viewed as a part of the community. This information is held by the various community members and is a valuable resource for outside consultants to tap into, particularly for those consultants that come from different geographic locations.

Not only can public input be utilized in a project to understand the greater context of a site, but the process of stakeholder involvement can also be a means to create community. Termed placemaking, it is the building and strengthening of community through the design and creation of everyday places. It involves the incorporation into the design process those who will be directly impacted by a project's construction. This can create a strong sense of community between those members, which in turn generates buy-in into the project as these individuals can become advocates for the project. Placemaking also establishes a sense of stability, by creating relationships between people and the project and people to each other [11].

Placemaking is fostered when the input of the community members is directly incorporated very early into the design process. The community-based design approach that builds upon the work of Schneekloth and Shibley [11], Hester [12], and Sanoff [13] takes advantage of the varied expertise, backgrounds, viewpoints, and attitudes of the local constituents. This input helps to develop a critical framework for a project.

Community-based design is distinguished from basic public input utilized in many projects. With public input, open meetings provide opportunities at predetermined intervals for the gathering and review of preconceived plans under development and the documentation of community commentary on those proposals. While this meets the standards for participatory design, it is reactionary and limits the ability for community ideas, details, and critical information to be fully incorporated into the actual design of the project. It misses the opportunity for incorporation of unique perspectives and solutions based on those perspectives that could have been revealed through a true community-based design process.

To take full advantage of the placemaking process, community members must be included in the charrette process discussed earlier. As participants in the charrette, they should be viewed as equal participants to professionals and other stakeholders, with their ideas and concerns given serious consideration with those of others. This requires a skilled facilitator and a structured decision-making process. This creates a significantly higher level of engagement by the community where community members offer suggestions or alternatives based on their understanding of the place and issues. If the setting allows for the full and open discussion of the issues, consensus may be better able to be achieved as individuals will be more likely to understand why decisions are being made [13, 14].

With great potential to assist in project advancement, coordination, and placemaking, charrettes do have some issues that need to be considered in the course of a project. Since they tend to happen early in the process, some issues that impact the design may not have been identified yet or may not be able to be fully explored in a short time frame [15], for example, the structural implications of construction approaches on existing subsoils. Additionally, charrettes can be dominated by individuals who can quickly, prolifically, or more clearly articulate their ideas. To address this, the charrette facilitator needs to make sure that all participants are equally heard [16].

Charrettes also take significant planning and effort to deliver, which costs time and money for clients. Space typically needs to be rented, food provided, equipment reserved, and travel and lodging arranged. These costs can add up quickly. It can also take several months to prepare for the charrette and then weeks or months to debrief and summarize the findings of the charrette itself, so there are design fees involved as well [16]. Additionally, charrettes can be ineffective if they are not well planned. Lack of clear goals and expected outcomes, the absence of key stakeholders or professions, and the inclusion of unnecessary or ineffective participants can limit potential outcomes. Effective charrettes tend to then be best facilitated by those with prior experience.

15.5 Sustainability

Many projects incorporate “sustainability” into design. Applied to a broad range of projects from small-scale efforts such as local composting and recycling programs to regional, state, national, and international projects that protect watersheds and address the issues of climate change, sustainability is still a nebulous term. It is generally without meaning or impact until specifically defined.

Sustainability is ultimately place specific, as the issues of one region vary significantly from other regions. An example of this is stormwater management. Areas with more significant rainfall (e.g., the Northwestern or Northeastern United States) may focus on peak flow control through BMPs and green infrastructure, while drier parts of the county (e.g., the Southwestern United States) may focus on rainwater harvesting for reuse. It is therefore incumbent upon the client and design team to clearly articulate what sustainability means for their project and the geographical landscape in which that project is located.

Typically, a sustainable initiative is any project, product, or program that is implemented to meet a site program element while also benefiting society by reducing harmful impacts to the environment. In urban areas, sustainability is inextricably linked to changes in population. Exponential increase in global population and the migration of populations from rural to urban areas over the past century have created urgent needs to rethink what sustainability demands. Design for conservation of energy and water, in particular, and effective management, reuse of waste, and careful planning for habitat are critical. At the outset of a project, agreement among stakeholders about sustainability outcomes and goals should be established so that the design team can incorporate these into the project throughout the process. Sustainable initiatives can be costly to add after the fact but, when incorporated throughout the project, can typically be implemented in a more cost-effective manner [4].

As for placemaking, Sandercock [17] has argued that community-based design is at the heart of creating sustainable places. The achievement of sustainability goals requires commitment from all community members as many sustainable practices require cultural change in order to be successful, which in turn may require changes in individuals' behavior or practices. One example is the implementation of a community composting program, such as can be found in Rochester, New York. Programs such as these require a change in mind-set of the individual. They will sort rather than collectively discard waste and incorporate new elements to their home (e.g., inside and outside compost containers). The presence of outside compost containers could be met with resistance by the community if they haven't been bought into the decision process. This, in turn, would diminish the efficacy of the program and dilute or prevent the achievement of sustainability goals.

Many sustainability initiatives are the result of regulatory mandates at all levels of government, due in part to an understanding of the benefits these initiatives provide to alleviate the physical strain on an aging and overburdened infrastructure and to minimize or offset the costs of replacing existing systems. For example, water quality protection and water quantity management that are part of such programs such as the US National Pollutant Discharge Elimination System (NPDES) guidelines are somewhat universal within the United States. Mandates to protect wetlands and streams are also common. Other elements that fall under the sustainability category may be regionally important and can include such things as energy use guidelines, brownfield redevelopment, heat island effect, and dark skies initiatives.

Complementing these mandates, business owners and developers are recognizing the public's demand for "green" design and are implementing sustainability initiatives for marketing purposes [18]. In answer to this demand, clients may include sustainability outcomes as part of the design program, such as energy independence or reduced energy expenditures on building performance and site maintenance operations.

Goals for sustainability in the urban ecosystem could address aspects of energy use, stormwater management, water consumption, infrastructure requirements, construction and maintenance practices, vegetation management, user comfort, spaces where people can meet their neighbors, and a host of other issues. Specific sustainability initiatives will then address these goals, for example, providing for the installation of bioretention and other infiltration techniques to alleviate stormwater runoff issues, the installation of solar photovoltaic systems to reduce reliance on fossil fuels, and the administration of composting and recycling programs to reduce inputs into the waste stream. Researchers and activists are also exploring how to incorporate food production and wildlife habitat into the urban fabric.

Sustainability designers cite global energy and water limits as reasons to rethink the urban ecosystem entirely. Williams [19] calls for urban designers to no longer think about limiting nonrenewable resource use but instead consider how to eliminate nonrenewable resource use altogether. In this approach, projects are not simply placed locally but are rather placed within their bioregional context in order to optimize renewable resource use and effectively work toward eliminating the use of external resources. The design style, materials, and approaches to construction should then originate in the bioregion of the project and consider the relationship between various project components in the context of the place. The intent here would be to optimize the design using the inherent knowledge of the bioregion. System components such as food, water, and energy would be planned to reuse waste flows from one component as system inputs into another component. An example of this is the use of stormwater runoff from a building roof (generally considered a waste product) for irrigation and for toilet flushing.

The Oberlin Project led by David Orr is one example of these interrelationships being incorporated into design. In a 13 acre neighborhood in Oberlin, Ohio, this is a collaborative project between the city and Oberlin College where urban revitalization, green development, advanced energy technology, urban agriculture, green jobs, and education are all being linked at the planning stage in order to re-envision urban ecosystems [20]. At larger scales, urban design for sustainability is currently being implemented as part of the eco-city movement that seeks to have regionally based economies and resource use in broad urbanized areas. This effort includes cities like Stockholm, Sweden, and Seattle, Washington, in the United States, both of which have set goals to be carbon neutral by 2050. New cities like Masdar City in Abu Dhabi and Dongtang in China are being planned and constructed with both water and energy conservation as key components. Although construction in Dongtang was suspended in 2008 [21], the city was expected to support a population of half a million on renewable energy. Masdar City is seeking carbon neutrality in one of the most oil-rich areas of the world [22].

While these goals are laudable, the question remains as to whether these initiatives are truly reducing environmental impacts. There is a movement in sustainability planning to quantify the degree to which that is the case. While each of these initiatives may individually contribute to the reduction of specific and localized impacts to the environment, the incremental nature of their implementation compared to the absolute magnitude of total material and energy flows in urban areas makes it difficult to fully ascertain a significant improvement toward the achievement of sustainability goals. M'Gonigle and Starke [23] defend the benefits of small changes that build upon each other, using the term incremental radicalism. However, it is difficult to say that any one change has made the urban area overall significantly more sustainable.

Quantifying sustainability is challenging due to the unique characteristics of each initiative, site, and environmental impact. Each initiative may have a distinct unit of measurement that makes direct comparisons cumbersome; for example, rain gardens may use cubic feet per second as a base unit, and wind turbines are typically measured in megawatt hours. Costs of installation can be compared; however, it is difficult to say if a wind turbine is more sustainable or makes a greater contribution to sustainability than does a rain garden, particularly when the factors of production are introduced. Trade-offs may even exist among sustainability efforts. For example, the planting of large trees to decrease energy use and improve air quality precludes installing solar PV on low buildings [24]. There may be a significant amount of energy involved in the production, shipping, and installation of the components required to produce each initiative.

15.6 Sustainability Metrics

To make the claim for improved sustainability, metrics or means to quantifying the improvement have been developed, often utilizing proprietary criteria that are applicable to specific project types. Established rating systems like the US Leadership in Energy and Environmental Design (LEED) and emerging systems such as the Sustainable Sites Initiative (SSI) and the Association for the Advancement of Sustainability in Higher Education's (AASHE) Sustainability Tracking, Assessment and Rating System (STARS), among others, provide methods to assess the relative sustainability performance of projects against recognized benchmarks. These metrics use accumulated points, or credits, to arrive at an indication of sustainability. A key aspect of these metrics is that they work to assess designs that look at buildings, sites, and/or systems holistically [4]. These metrics define categories for the relative levels of implied sustainability and provide flexibility for owners and designers as they make decisions as to which sustainability initiatives to include in design solutions.

Although similar in their use of point-based systems, these metrics are foundationally different. LEED, for example, is a market-driven effort with a vision that "buildings and communities will regenerate and sustain the health and vitality of all life within a generation" [25]. While the system is evolving to consider neighborhoods and the urban ecosystem holistically, the focus is still largely on new or substantially renovated buildings. The LEED rating system places most emphasis on efficient energy, air quality, and water use within these buildings [26]. In contrast, SSI was developed by the American Society of Landscape Architects, the Lady Bird Johnson Wildflower Center, and the US Botanic Garden. This rating system focuses on ecosystem services provided by the landscape, irrespective of buildings [27]. While LEED includes a component for sustainable sites, that metric focuses on strategies that minimize the impacts on nature rather than on optimizing the services provided by nature (e.g., water regulation), such as is encouraged with SSI.

These point-based systems must be used with a clear recognition of the limitations of the methodology. Point-based methodologies, such as LEED and SSI, have been criticized as not giving an accurate assessment of the environmental sensitivity of a project. Schendler and Udall [28] point out that the subjective selection of points creates the potential to deprioritize critical aspects of sustainability that may be difficult or costly to achieve, such as not pursuing brownfield sites for redevelopment or choosing to accept lower energy performance levels. They also note that the technical advisory committee process by which LEED standards are developed diminishes their strength due to the negotiated nature of committee decisions. LEED buildings are not consistently and measurably more sustainable. Newsham et al. [29] looked at 100 LEED-certified buildings and found that while on average LEED buildings used as much as 39% less energy, more than a quarter of these buildings use more energy per square foot than their non-LEED counterparts. Thompson and Sorvig [30] also highlight the varying regional issues of sustainability and that a standardized system of assessment may not be able to fully account for this. LEED has in part addressed this with some points available for locally important issues, but these are based at the regional rather than site level.

In spite of their differences and potential limitations, LEED and SSI have been increasingly incorporated into site projects. These metrics have proven valuable in the promotion and advancement of sustainable design and have raised the consciousness of sustainability in the design professions and with developers, community stakeholders, government agencies, and regulators. We describe below two projects, which highlight the use of these systems.

The Gateway Center at the SUNY College of Environmental Science and Forestry in Syracuse, NY, USA, was developed using the LEED-NC (new construction) system. The building replaced a parking lot at the main entrance to the urbanized campus. Nearly 20,000 sq. ft. in area, it contains the college's admissions and outreach offices, hosts small conference events, and has student life functions including the college bookstore, café, and gathering space. This project achieved a LEED-Platinum rating (the highest rating possible) on the strength of multiple sustainability initiatives. Central to these initiatives is a wood pellet-powered energy system designed to provide energy to five buildings on campus. This helps address a significant factor of sustainability (energy) by making the Gateway Center substantially independent of the electrical grid. Other initiatives include the provision of open space, mitigation of heat island effect, extensive stormwater management

Fig. 15.10 The green roof at Gateway Center in Syracuse, NY. The image highlights the use of plants from native plant communities (alvar grassland and Eastern Ontario dune) that provide enhanced pollinator services throughout the year. (Source: Tim Toland)

facilities, minimal potable water use, use of local materials, super-insulated building envelope, and enhanced indoor environmental quality (e.g., automated solar control for heat gain management) (Fig. 15.10).

Another project is the Shoemaker Green in Philadelphia, PA, USA, that earned two stars (out of four possible) from the Sustainable Sites Initiative. The project is a 2.75 acre open space on the University of Pennsylvania campus that transformed aging tennis courts, narrow pathways, and obstructed views of a historic war memorial into a public amenity for the community. The site was designed to include seating and gathering space, flexible-use recreational space, connections to other campus locations, and a robust stormwater management system (Fig. 15.11).

Both of these projects utilized multidisciplinary and participatory processes discussed in this chapter. The Gateway Center was the first building project finished after the College completed a master plan in 2008. Through community input sessions during the master planning process, the campus faculty, staff, students, and administration generated a vision for the college that focused on the idea that all projects should demonstrate the mission and values of the college and focus on demonstrating environmental stewardship. Several Gateway Center project initiatives (e.g., maximization of on-site stormwater management, minimization of turfgrass, provision of habitat plantings, use of local materials) were borne from ideas gathered

Fig. 15.11 Shoemaker Green in Philadelphia, PA, highlighting the two-tiered rain garden and expansive green space (Image source: Andropogon Associates, with permission)

during those sessions. Shoemaker Green began with an in-depth site assessment, exploring the site's history, context, ecological structure, and functional capacity. The design was sensitive to user's needs and requirements, considering the hours and seasons that the green would be occupied. A diverse stakeholder group, including representatives from within the University, Philadelphia agencies, and the design community, refined the final design through a rigorous review process.

Both of these projects also made stormwater management a central focus of the design. The Gateway Center's system includes a native plant-based green roof, bioretention cells, street bioswales, and subterranean storage cells. These are connected in a treatment train that outlets water from one space to another and maximizes opportunities for storage, infiltration, and evapotranspiration. Shoemaker Green's stormwater is managed in two ways. The first strategy conveys stormwater runoff to a large, two-tiered rain garden; the second strategy collects runoff from the site as well as runoff from the roof and condensate from adjacent buildings, releasing the water into the soil under the main green which percolates to a large storage bed several feet below the green. Any excess water that is not taken up by the soils and plants is captured in this bed through an underdrainage system and conveyed to a large cistern and stored for reuse. With these projects only very large storm events release water to the municipal systems.

These projects highlight how systems thinking, i.e., considering how one project component connects to and provides input into other project components, can allow even small sites to have improved environmental functioning. With this approach, relationships between natural systems (e.g., soils, plants, wildlife) and human systems (e.g., buildings, infrastructure) allow the whole site to function more as a natural system would. Both projects enhance ecosystem services while also providing for their primary functions as liveable spaces on their respective campuses.

LEED and SSI generally focus on the construction of a project, with some consideration given to the operations and maintenance of a site post-construction; however, there are no ongoing assessment mandates required for certification with these metrics. Life cycle assessment (LCA) and emergy evaluation are far less common sustainability metrics for urban ecosystem design. Nonetheless, these metrics could fill the gaps in sustainability assessment that exist with LEED and SSI. This includes the full evaluation of the sustainability impacts of a project from inception to demolition (also known as cradle to grave).

Life cycle assessment (LCA) is a tool for quantifying the overall cradle-to-grave environmental impacts from a product, process, or service [31, 32]. It considers the entire system in an evaluation, including the extraction, transport, manufacture, use, and ultimate replacement and/or disposal of each design component being analyzed. The primary goal of LCA is to choose the best product, process, or service with the least effect on human health and the environment, considering such factors as resource procurement (e.g., mining), manufacturing, shipping, maintenance, demolition and disposal. When deciding between two or more infrastructure alternatives, LCA can help decision-makers compare all major environmental impacts caused by products, processes, or services and select the product or process that results in the least impact to the environment. LCA data identifies the transfer of environmental impacts from one media to another (e.g., eliminating air emissions by creating a wastewater effluent instead, such as would occur with a wet scrubber) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition phase). As a note, LEED version 4 contains an optional credit for considering life cycle in design.

Emergy evaluation is a comprehensive sustainability analysis process that considers buildings, places, natural components, and human activities as part of a holistic system rather than as isolated projects. Unlike most other sustainability metrics, emergy, sometimes referred to as embodied energy, considers the whole balance of flows to a system, from energy to water to food. In order to understand system flows, emergy evaluation quantifies values of natural and economic resources on a common unit basis to derive the value of nature to the human economy [33]. These inputs are synthesized into concise metrics of sustainability, such as the emergy sustainability index (ESI) and the environmental loading ratio (ELR). These metrics in differing degrees quantify the level to which a project takes advantage of renewable resources and ecosystem services, relative to resources fed from the economy, which might include fossil fuel energy, labor, and materials. This holistic systems approach helps to fully understand how each component of a project either contributes to or detracts from sustainability goals and the emergy sustainability metrics [34]. A designer could conceivably communicate with a client the level at which "free" resources are utilized by the project and also which components create the greatest overall drag on sustainability. For example, Rodriguez [35] showed how rain gardens, a form of green infrastructure, provided greater "free" renewable resources, reflected in a higher ESI, than gray infrastructure; she was also was able to differentiate between different green infrastructure alternatives. Whereas rain gardens eventually garner sufficient renewable resources (e.g., sunlight and rain) to warrant investment as a green infrastructure alternative, porous pavement was shown to never "pay back" the economic investment through renewable resource conservation and accumulation due to use of gray infrastructure in the base material (e.g., concrete) and extensive use of machinery. At the site level, Toland and Diemont [36] found that university campus "greening" at State University of New York College of Environmental Science and Forestry (ESF) resulted in considerable long-term benefit in renewable resource capture for the university. They were able to show that the investment that the university made provided a greater degree of sustainability. This increased sustainability was primarily due to reduction in energy use and conversion to more renewable energy forms.

An important part of emergy evaluation is its scalability. Urban ecosystems are within watersheds, which are then within larger regional ecosystems. Unlike LEED, SSI, and LCA, emergy evaluation can be modified easily to be conducted at several spatial levels, from site [37] to regional ecosystem [38] or at the scale of an entire state [39], to understand at which level the designer needs to modify system components at various scales in order to optimize system sustainability. Because the urban ecosystem is at the interface between nature and the human economy and combines natural resources and purchased inputs for designed changes, maintenance, and operation, emergy evaluation can be a very appropriate and useful tool for analyzing urban design. For instance, Tilley and Swank [38], working at a larger forest scale than Diemont et al. [40] included social interaction with the site in terms of forest visitors. Campbell and Ohrt [39] included the entire social infrastructure through, for example, government spending and money spent in tourism. This flexibility of approach allows designers and decision-makers to fine-tune investigations and investments based on the scale of interest.

In order to use effectively any of these metrics in a project, they must be incorporated into the normal workflow of the design process, first at the inception of the project, where project goals are defined, and then at each design interval to evaluate alternatives and finally to assess achievement of project goals. LEED, SSI, and other metrics contain guidance in the form of checklists and credit criteria that can be reviewed and utilized by various team members. LCA and emergy evaluation are more involved efforts.

While they may give more accurate representations of overall sustainability, performing an LCA or emergy evaluation can be resource and time intensive. Depending upon how thoroughly the user wishes to conduct the analysis, gathering the data can be problematic, and the availability (or lack thereof) of data can greatly impact the reliability of the final results. It is important to weigh the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits of each of these evaluations.

All sustainability metrics are, nonetheless, simply a starting point to sustainable holistic design. Each project must be taken on a case-by-case basis and the issues that are locally and regionally important emphasized and addressed by design solutions. Part of the mind-set of sustainable design is to seek some level of minimum performance; however, this may not maximize the lifetime sustainability of the building or site. The lifetime view needs to account for the entire embodied energy of the materials, renewable resources, labor, and fossil fuel energy used in a project and the impacts the project will have on behavior (e.g., Will more people bike to work than before?). While considerable thought is given to design and construction, ongoing operations, maintenance, and ultimately renovation and/or demolition also have significant sustainability impacts. Some sustainability criteria, such as reductions in energy use, should be pushed beyond minimal levels during design as this accounts for a majority of the embodied energy of building over its lifespan. Scheuer et al. [7] suggest that over 94% of the embodied energy is in the form of electrical and HVAC systems. Designers need to acknowledge the enduring impact their ideas and recommendations have on sustainability of the long term.

15.7 Conclusions

With any site project, the client initiates much of the activity that occurs in a project. The investor takes the risk in acquiring the property and expending the capital for its improvement and profit from the project's success. Multiple professional perspectives are required to implement the project, and many factors need to be considered to ensure a successful project outcome, particularly those that have multiple complex systems and project goals. This is best achieved when (1) an interdisciplinary or collaborative charrette approach is used, (2) stakeholder and community input is solicited via the community-based design process, and (3) assessments of alternative solutions (e.g., using sustainability metrics) are employed to determine which of many possible sustainability elements will make a greater contribution to long-term project sustainability goals.

While in many instances the client will be aware of factors such as stakeholder and community input requirements and sustainability metrics, designers shouldn't assume they know about these things in depth. Where required by regulatory statute, these steps can seem like an unnecessary burden to the design and development process. However, consultants can be advocates for incorporating stakeholder and community input requirements and sustainability metrics, into the process by recognizing the benefits that can accrue from them. This input can be critical to more clearly and definitively reach social, economic, and environmental goals and to develop solutions that integrate well into the community thus enhancing its social-ecological metabolism.

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Chapter 16
Epilogue

Stephen B. Balogh

Abstract This chapter reviews the major themes and insights of the book and provides a glimpse into cutting-edge and future research in urban ecology.

Keywords Resilience · Social-ecological-technical systems · Big data · Visioning · Collaboration

16.1 Introduction

We have titled this final chapter “Epilogue.” An epilogue is used normally at the end of a play or literary work to summarize what has happened or been covered in the work and sometimes to report what has happened later to the characters after the writing stopped. That is our intent here, first to summarize what has been covered in this book and then to look forward at recently conceptualized or developed programs, policies, and technologies intended to achieve a more sustainable, more resilient urbanized world.

16.2 Looking Back

Looking back, we find that as was our intention the preceding 15 chapters have provided the background science, insights, and methods needed by citizens to examine and understand cities from a systems perspective. Through readings, discussion, and lab exercises, students and their teachers have had the opportunity to be immersed in the thinking about the structure and function of the biotic and abiotic components and subsystems that comprise urban areas, and the interactions

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between them. Hopefully we've helped readers identify links between cities and the rest of the natural and human influenced world that they might not have considered before. We have shown how the quantification of the flows of energy and materials reveals the dependencies that affect the viability of urban life now and into the future (Chap. 1). We've described the role of human actors, their communities, and institutions in shaping, maintaining, and even transforming our biophysical and social realities and we have considered how our perceptions and expectations of urban life have evolved over time (see, e.g., Chaps. 2, 3, 4, 5, and 14).

We've explained how geological (Chap. 2), hydrological (Chap. 6), and climatic (Chaps. 7 and 8) factors helped determine where cities were first established and how their design and social-ecological/socioeconomic metabolism (operation) evolved through the ages. We've looked at *ecology in* cities with respect to how the process of urbanization changes the environment and hence the diversity of plants and animals that can survive in urban areas, their adaptations through evolution, and the creation of novel ecosystems (Chaps. 11 and 12). We've stressed the importance of humans' increasing ability to harvest solar and then fossil energy in the development of cities and, in turn, how increased access to energy shaped our social arrangements, our economies, and our well-being (Chaps. 2, 4 and 5).

Throughout the book, the authors, experts in their fields, have described many of the present and future challenges which urban residents face—climate change, resource restrictions, pollution (Chaps. 2, 5, 8, and 9), food production and distribution (Chap. 14), and health consequences—but also power and wealth imbalances (Chap. 5), environmental injustice (Chap. 13) and threats to urban support systems such as land use change (Chaps. 3 and 6), food production and eutrophication of waterways (Chaps. 6 and 9), as well as the impacts of our consumption in terms of solid waste (Chap. 10). By conceptualizing cities as complex adaptive ecosystems, we acknowledge the uncertainties in attempts to intervene in these systems and how as self-organizing systems they may react to those interventions.

To help students face these and other challenges, we have provided a holistic systems perspective that includes new tools for organizing our mental models of what a city is and does, a variety of approaches to collaborate in the creation of conceptual models of social-ecological systems, and ways to identify important feedback loops and intervention points through simulation modeling and participatory urban planning and design strategies (Chaps. 3 and 15).

16.3 Looking Forward

Important progress continues to be made in our understanding of cities as ecosystems, in technologies used to collect and process information, and in the social and ecological sciences that investigate the interdependence of humans and nature. These "unresolved plot lines" deserve mention here.

16.3.1 Big Data and "Smart" Cities

The potential for informing our understanding of coupled human and natural systems through collecting and analyzing data is beginning to grow by leaps and bounds. Advances in computer data storage and processing power, combined with ubiquitous Internet and cellular phone connectivity, have resulted in an era of "big data," whereby extremely large datasets can be compiled and mined for interesting patterns and trends. Sensors designed to measure air and water quality, meteorological phenomena, foot and vehicular traffic, and other environmental and social data have been deployed throughout cities and relay information to end users in real time. Simultaneously, people are purposefully sharing information about their perceptions and values through social media, while communications and Internet media companies track users virtual and real-world locations.

The city of Chicago, for example, is currently harnessing big data to create a *smart city*, defined as the use of "computing technologies to make the critical infrastructure components and services of a city—which include city administration, education, healthcare, public safety, real estate, transportation, and utilities—more intelligent, interconnected, and efficient" [1]. This includes the Array of Things (AoT), described as an "urban sensing project" comprised of a network of interactive, modular sensor boxes installed around Chicago to "collect real-time data on the city's environment, infrastructure, and activity that will be made available both for scientific research and public use." AoT has been described as a "fitness tracker" for the city, measuring factors that impact health and well-being such as climate, air quality, and noise. The goal of this project is to inform scientists, engineers, decision-makers, and residents in order to make the city "healthier, more livable, and more efficient" [2]. Projects like these are not without their detractors (see examples in [3]), many of which are concerned about city residents willingly or unwillingly trading their privacy for the benefits described by smart city promoters.

16.3.2 Climate and Coastal Resilience Efforts

Many cities, especially those vulnerable to sea level rise, tropical storms, changes in precipitation regimes, flooding, fire, and other impacts of climate change, have begun to assess their risk to these impacts. These cities have worked with residents, policy makers, academics, and other stakeholders to create strategies to reduce risks, plan for uncertainties, and resist, absorb, accommodate to, and recover from, hazards [4]. The Rockefeller Foundation has provided funding to 100 cities globally to increase their capacity to deal with the problems of the twenty-first century. In part this entails creating and hiring a Chief Resilience Officer and developing a resilience strategy [5]. Other cities are creating similar positions focused on resilience or sustainability. Many of these cities are particularly threatened by sea level rise or coastal flooding.

Fig. 16.1 A portion of the Metropolitan Area Outer Underground Discharge Channel in Tokyo © Flickr user "ptrktn" available from https://www.flickr.com/photos/ptrktn/3353015541

Historically, investments in coastal resilience took the form of large capital-intensive gray infrastructure projects such as the Thames Barrier, a flood prevention system installed in 1984 to protect the city of London, England, from storm surges and extreme tides, or MOSE, a multibillion-dollar floodgate system designed to protect the city of Venice, Italy, from extreme high tides. New Orleans continues to build up its system of dykes and pumps to prevent inundation and flooding. Tokyo completed the Metropolitan Area Outer Underground Discharge Channel in the 2000s, a massive underground flood water collection and storage facility used to protect the city from flooding during the rain and typhoon seasons (Fig. 16.1). Over 3000 miles of levees protect cities and towns along the Mississippi River.

Newer solutions are moving from traditional "fail-safe" infrastructure, like storm culverts and dykes, which has low likelihood but high consequences of failure, to the notion of "safe to fail" with more frequent failures but lower (less damaging) consequences [6–8]. These cities are designing systems which can act as sponges or divert flooding to natural corridors, away from vital infrastructure or vulnerable populations. The Indian Bend Wash in Scottsdale, Arizona (Fig. 16.2), is a greenbelt designed to provide access to greenspace, urban cooling, improved air quality from its urban forest, and bike trails during pleasant weather. The Wash also has the capacity to transport large quantities of water during precipitation events. At these times the bike paths and green spaces become a flowing river absorbing the overland flow from surrounding impervious areas [6]. Other coastal areas are building up "elevation capital" in coastal wetlands to protect inland cities and communities,

Fig. 16.2 Indian Bend Wash in Scottsdale, Arizona. Photo Credit: Nancy Grimm, with gracious permission

while still others, e.g., Staten Island in New York City, are working with frequently flooded communities such as those affected by Superstorm Sandy in 2012. By offering to buy out owners rather than have them rebuild, the City can expand coastal wetlands and provide a buffer of protection from storms.

16.3.3 Moving Conceptually from Social-Ecological Systems (SES) to Social-Ecological Technical/Technological Systems (SETS)

As technology has progressed and as strategies to address urban challenges begin to shift from risk avoidance to ecologically based systems, scientists are emphasizing the importance of built infrastructure in conceptual frameworks for urban systems. Recently urban ecologists, sustainability scientists, and others have begun to include technology as a coequal component to be differentiated from social and biophysical systems, thus moving beyond the SES framing to a social-ecological-technical system (SETS) framework for designing the built environment [9]. The impetus for broadening the conceptual framework stems from the recognition that urban infrastructure plays an important mediating role between human activities and the state of the environment. These investments in infrastructure may be long-lived and may either intensify human pressures on environmental systems or moderate them. In other cases, underinvestment or disinvestment in infrastructure can be detrimental to human health and well-being (e.g., inadequate sewer collection and treatment facilities or aging and heavy-metal contaminated drinking water distribution systems). Certainly, in this book we describe the historical importance of technology in development of our economic systems (Chap. 5), in many of the subsystems of cities (e.g., Chaps. 1, 6, 9, and 10), and even in the way the technologies we adopt may confound or mitigate issues of environmental justice (Chap. 13). As we have stressed in our final chapters, solutions to complex urban problems will require decision-makers to collaborate with environmental scientists and ecologists and also with citizen groups, engineers, designers, planners, and architects to figure out ways to integrate our green and gray infrastructures and take advantage of new ways of collecting, processing, and visualizing data [9].

Collaborative planning meetings, such as those described in Chap. 15, as well as newer "visioning workshops" like those in progress in cities being studied by the Urban Resilience to Extremes Sustainability Research Network (UREx-SRN) operationalize the SETS concept. Like traditional collaborative work, these meetings are designed to include a wide range of stakeholders and decision-makers. Workshops bring together decision-makers, planners, and experts to create teams that approach projects from a systems point of view that recognizes the interdependencies and feedbacks both from social and ecological perspectives and continue to do so throughout the planning process (Chap. 15). The UREx-SRN process addresses resiliency and sustainability at the level of the city rather than individual projects, with transformative change as the goal. It includes not only government officials, scientists, engineers, and architects but also artists, community leaders, educators, and others to co-produce a broader suite of outputs: conventional data and conceptual models but also stories, maps, and images. Maps, drawings, and technical sketches are produced on the fly from the participants' ideas about resilient, sustainable cities that provide ecosystem services, improve social well-being, and exploit new technologies in ways that benefit all segments of urban populations [10]. These qualitative and quantitative data can then be used by modelers to explore with sensitivity analysis possible pathways to these co-developed futures.

16.4 Conclusions

As we stated in the preface, it is our hope that now that you have finished this book, you will go out into your professional life with a greater appreciation of the amazing complexity of the urban ecosystem, and with a better understanding of how the biotic and abiotic components of the urban ecosystem interact and adapt (or fail to adapt) to changing conditions over time. With that knowledge we hope you will be inspired to become a participant in some of the emerging efforts we have described above or a creator of novel solutions, whether social, ecological, or technical, that will help make the cities of the future resilient to the environmental changes they are currently undergoing and will continue to encounter. We do not wish to leave you with the impression that this task will be easy. The world's population continues to grow requiring ever more housing, infrastructure, and resources. Whether our current urban areas, new urban areas, and our planet of finite resources can absorb this growth is the monumental challenge. Do not look for, nor expect, easy solutions. Rather, apply your understanding of urban ecology to help you evaluate the best way forward. Humans are by nature problem solvers [11], but we must ask of the solutions available, what will endure and what will enhance life on Earth?

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