Global Population Distribution and Urban Land Use in Geophysical Parameter Space

Christopher Small*

Lamont-Doherty Earth Observatory, Columbia University, New York, New York

Received 6 October 2003; accepted 22 December 2003

ABSTRACT: The spatial distribution of human population on the land surface is a fundamental determinant of land-use impacts on Earth's ecosystems. Census enumerations and satellite-detected night lights provide two complementary, but distinct, representations of human population distribution. Census estimates indicate that 37% of Earth's enumerated land area is populated at densities greater than 1 person per square kilometer. Human populations are strongly clustered within this area. Spatial variations in human population density span more than six orders of magnitude with 50% of the 1990 population occupying less than 3% of the inhabited land area. Temporally stable lighted areas detectable from space provide an independent proxy for the spatial distribution of urban settlements and the intensive land-cover changes that accompany them. These ~60 000 lighted areas account for less than 2% of inhabited land area, and 50% of this lighted area is associated with the largest 5% of cities and conurbations. Urban land use associated with higher population densities can exert a disproportionate influence on environments both near and distant. The spatial distributions of population density and lighted areas relative to geophysical parameters (continental physiography and climate) highlight some similarities and differences in the relationship of urban and rural land use to different physical environments. The spatial distribution of urban

* Corresponding author address: Christopher Small, Lamont-Doherty Earth Observatory, Columbia University, New York, NY 10027–6902.

E-mail address: small@LDEO.columbia.edu

land use is strongly localized with respect to continental physiography (coastal and fluvial proximity and elevation) but much less localized with respect to climatic parameters (annual mean and range of temperature and precipitation). These distributions quantify the extent to which spatially focused development of urban land use, with respect to the physical landscape, influences coastal and riparian ecosystems in particular. If future population distributions follow current patterns, then demographic momentum and increasing rates of urban migration will result in accelerated growth of urban areas in these environments.

KEYWORDS: Population, Urban, Land use

1. Introduction

Current population growth is being accompanied by a significant change in human habitat. As an increasing number and fraction of the global population live in urban areas, the physical environment inhabited by humans is rapidly changing. This change is likely to influence both human populations and the ecosystems where the populations are concentrated. The global population growth rate is currently decreasing, but demographic momentum implies that population growth will continue, according to most forecasts, until at least the year 2100 (O'Neill and Balk, 2001). At the same time, widespread urbanization has the effect of concentrating the growing population into dense settlements at unprecedented rates (Meyer and Turner, 1992). Near-term (<50 yr) population growth is expected to occur primarily in moderate-sized urban areas of developing countries maintaining high birth rates (United Nations, 2001). This represents a relatively recent change of physical habitat for humans as well as a change in the nature of human impact on specific ecosystems. Dispersed agrarian populations influence different ecosystems in ways that are different from how dense urban populations influence them. Cities and their surrounding communities exert influences (i.e., physical, political, socioeconomic) disproportionate to their relatively small areas.

Understanding the systematics of present and future human population distribution is critical to understanding the impacts that population growth could have on the rest of the Earth system in the future. Human transformation of Earth's ecosystems is now recognized to be areally significant (e.g., Cincotta et al., 2000; Vitousek et al., 1997; Turner et al., 1990), but the majority of the human population inhabits a relatively small area. In 1990, over 50% of the human population occupied less than 3% of the ice-free land area (Small and Cohen, 1999; Small and Cohen, 2004). The impact of high-density urban land use is different from the impact of low-density agricultural land use. On a global basis, urban land use may be areally insignificant, but at local and regional scales the large material and energy fluxes associated with urban areas have a disproportionate impact on microclimate and ecosystem function (e.g., Berry, 1990; Landsberg, 1981). Regional analyses have demonstrated that urban NO_x emissions are volumetrically significant enough to have an adverse impact on regional agricultural productivity (Chameides et al., 1994). Urban heat island effects are also believed to be responsible for inducing atmospheric convergence sufficient enough to influence thunderstorm formation and movements observed near large urban areas (Bornstein and LeRoy, 1990; Bornstein and Lin, 2000). Regional climate models also indicate a strong sensitivity to land-cover variations at scales of kilometers (Pielke et al., 2002; Roy and Avissar, 2000; Li and Avissar, 1994), which suggests that urban land-cover conversion may significantly modify local and regional climates. The effects of human settlement patterns on other ecosystems have long been recognized, but the extent of their impacts is only now beginning to be understood.

The objective of this analysis is to quantify some basic characteristics of the spatial distribution of human population and urban land use with respect to physical environments. While the qualitative characteristics of human population distribution are well known, few of these characteristics have been accurately quantified. This can be accomplished by estimating distributions of population and urban land use as functions of multiple geophysical parameters. This analysis attempts to quantify some systematic patterns and to highlight differences between urban and rural populations and the physical environments where they occur. Many of the results presented here are based on the analyses of global population distribution by Small and Cohen (Small and Cohen, 1998; Small and Cohen, 1999; Small and Cohen, 2004). In addition, the spatial distribution of urban land use is inferred from stable night lights observed in 1994/95 (Elvidge et al., 1997a; Elvidge et al., 1997b). The distributions of population and urban areas relative to physiographic and climatic parameters can indicate which environments may be most directly impacted by present and future population distributions. Differences in the distributions of population and urban land use can highlight differences in urban and rural populations. These differences may be significant because urban and rural land uses have different impacts on the ecosystem's function.

2. Spatial distribution of population and urban land use

2.1. Census data

At global scales the spatial distribution of human population must be inferred from proxies. Gridded compilations of census data provide spatially explicit numerical estimates of human inhabitants, but the accuracy and spatial resolution vary considerably from one country to another (Tobler et al., 1997). Results presented here are derived from version 2 of the Gridded Population of the World (GPW2) dataset [(Center for International Earth Science Information Network) CIESIN, 2000]. Gridded estimates of population count and population density (people per square kilometer) are based on a compilation of populations and areas of 127 105 political or administrative units derived from censuses and surveys (Figures 1 and 2). The range of census years used was 1967–98, and all populations were projected to a common base year of 1990 to yield a global population of 5 204 048 442 people. The uncertain accuracy of the census data implies considerable spurious precision in this total. Population counts are assumed to be uniformly distributed within each administrative unit and are sampled on a grid of 2.5 arc min (2.5′) quadrilaterals (Deichmann et al., 2001). The median spatial resolution of the input census data is 31 km. A detailed description of the spatial properties of this dataset is provided by Deichmann et al. (Deichmann et al., 2001)

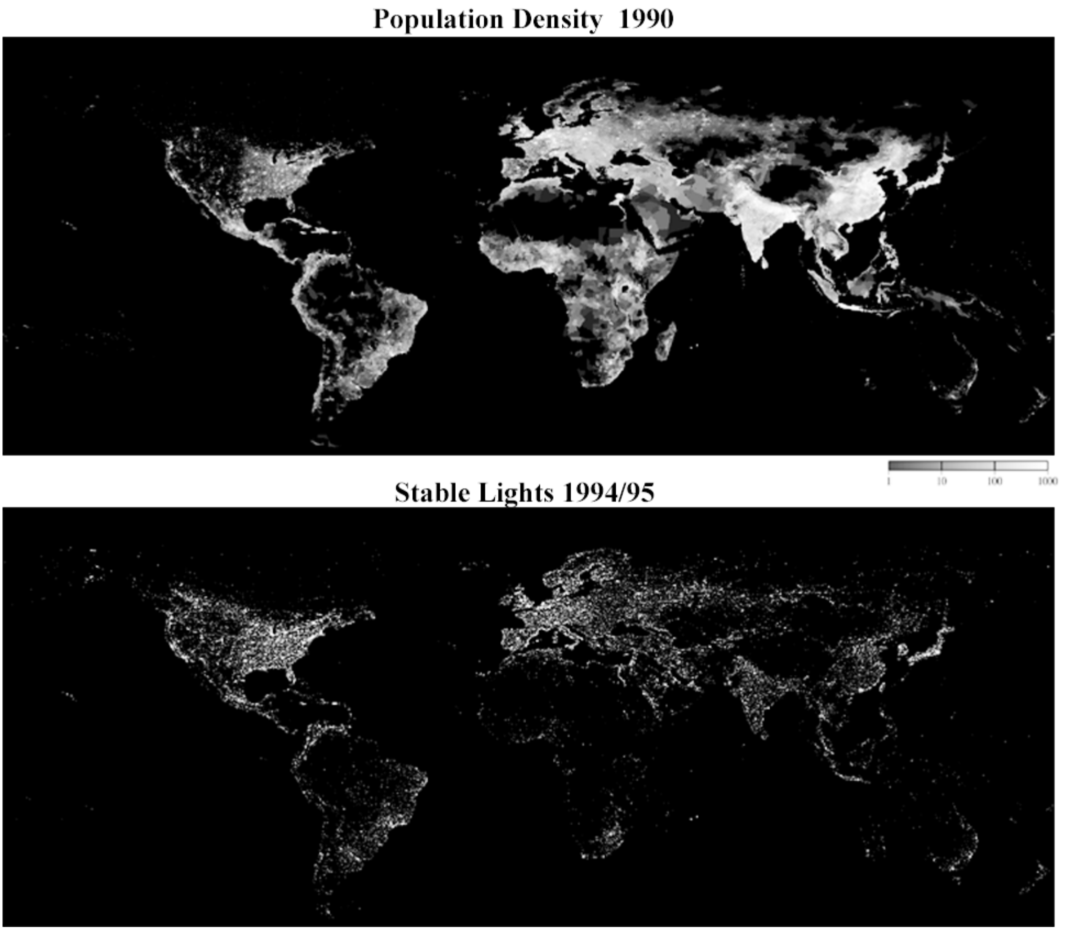

Figure 1. Global distributions of population density and lighted settlements. (a) The 1990 population density, derived from the GPW2 census compilation (CIESIN, 2000), ranges from 1 person per square kilometer (dark) to 1000 people per square kilometer (white) on a logarithmic scale. Lower and higher densities are saturated black and white, respectively. (b) Temporally stable lights are indicated by frequency of occurrence (100% white) are derived from DMSP/OLS nighttime satellite imagery collected in 1994/95 (Elvidge et al., 1997a). Gridded population densities provide estimates of the spatial distribution of population while stable lights provide a higher-resolution proxy of the spatial distribution of population centers and socioeconomic activity.

and Small and Cohen (Small and Cohen, 1999; Small and Cohen, 2004). For the purposes of this analysis, all populated areas included in census enumerations are considered to be potentially habitable land areas. This excludes Antarctica and some areas at high northern latitudes.

As represented in GPW2, global population density varies by more than six orders of magnitude (Small and Cohen, 1999; Small and Cohen, 2004). This is a minimum estimate because populations are assumed to be uniformly distributed

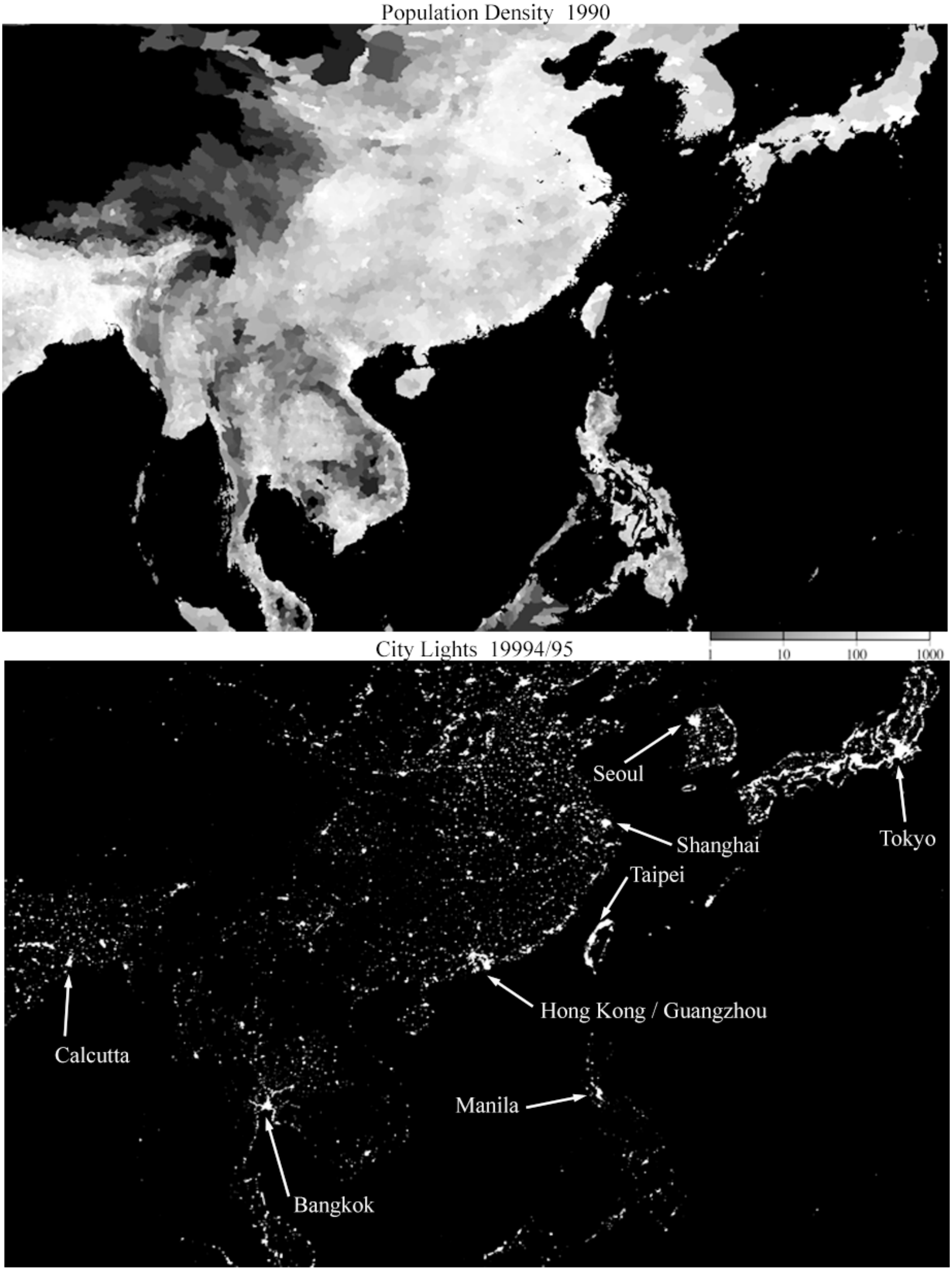

Figure 2. Population density and city lights for southeastern Asia. Data sources and gray scaling are the same as in Figure 1. (Note spatially extensive lighted areas in Japan and Taiwan as well as large conurbations around Seoul, Bangkok, and the Pearl River delta in southern China.)

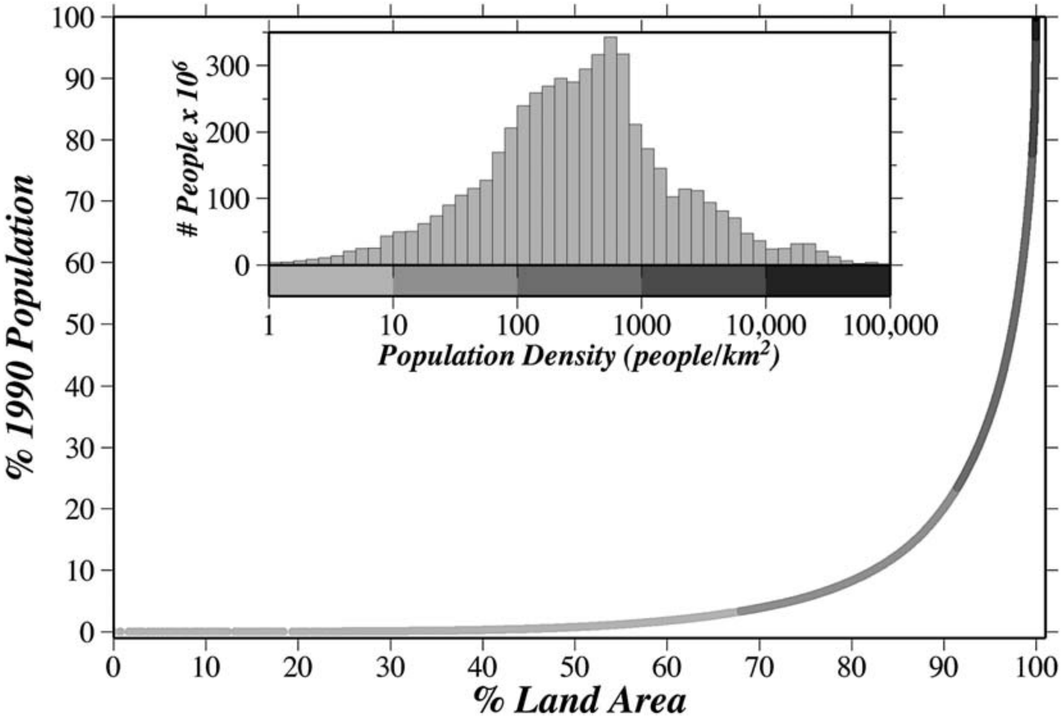

Figure 3. Global distribution of people as functions of population density and land area. Inset histogram indicates that most people (54%) live at densities between 100 and 1000 people per square kilometer, but the density-shaded spatial Lorenz curve shows that this 54% occupies only 8% of the inhabited land area while the densest 50% of the population occupy less than 3% of the land area at densities greater than 300 people per square kilometer.

within administrative units. Night light data (discussed below) and direct experience suggest that that there is considerable clustering at finer spatial scales. Population maps are presented on a logarithmic scale to better represent the wide range of population densities. At global scales it is difficult to appreciate the extent of spatial clustering represented in the dataset. The extent of population clustering can be summarized with a Lorenz curve for the spatial distribution of population in the GPW2 dataset (Figure 3). This curve shows the cumulative sum of population as a function of the cumulative land area that it occupies when the quadrangles are ranked from lowest to highest population density. It is referred to as a spatial localization function to distinguish it from Lorenz curves describing population distribution with respect to nonspatial parameters. The curvature of the function indicates the degree of spatial localization. A linear localization function depicts a uniform distribution over all available areas. It is apparent from the curvature of the localization function that human populations are strongly clustered at the global scale. Figure 3 indicates that at least 50% of the 1990 human population occupied less than 3% of Earth's potentially habitable land area. The converse is not necessarily true however. Because there are often local settlements within the low-density administrative units, the sparsely populated areas have low densities on average but may contain small concentrations of higher-density settlements that are not spatially represented in the census data. Nonetheless, it is still accurate to say that half of Earth's potentially habitable land area is sparsely populated, containing less than 2% of the human population at densities of less than 10 people per square kilometer.

2.2. Night lights

Satellite maps of anthropogenic night lights provide an additional source of information on the spatial extent of urban land use. The Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) has provided observations of the location and frequency of occurrence of visible and near-infrared (VNIR) emissions from fires, lighted human settlements, and other anthropogenic sources since 1972 (Croft, 1978). These data have been compiled and processed to provide a unique measure of the location and spatial extent of human settlements in 1994/95 by Elvidge et al. (Elvidge et al., 1997a; Elvidge et al., 1999). Temporal persistence distinguishes stable lights associated with permanent settlements from intermittent emissions related to fires. The global distribution of lighted settlements is shown in Figure 1. From this dataset it is possible to derive estimates of the locations (centroids) and areas of contiguous lighted settlements worldwide. In discussions of distance and resolution, it is more intuitive to think of a linear dimension than an area so the size of lighted settlements is given in units of a circular equivalent diameter. A circular equivalent diameter is defined here as $2\sqrt{(\text{area}/\pi)}$. The size distribution and cumulative area of the light dataset is shown in Figure 4.

The use of lighted areas as a proxy for human settlement is subject to a number of caveats. A detailed comparison of the stable light dataset to higher-resolution (30 m) Landsat imagery indicates a detection threshold below which increasing numbers of lighted settlements are not imaged (Small et al., 2004, manuscript submitted to *Photogramm. Eng. Remote Sens.*). The limited spatial resolution (2.5 km) and sensitivity of the operational linescan system (OLS) sensor precludes detection of many small light sources (Elvidge et al., 2004). Atmospheric scattering and spatial uncertainty in geopositioning also diminish the spatial accuracy of satellite-detected night lights resulting in lighted areas somewhat larger than the associated settlements. Because the spatial extent of a lighted area is known to be significantly greater than the actual built-up area of many settlements (Elvidge et al., 1997a), discussions of area and dimension must account for overestimation. A recent comparison of lighted areas with Landsat imagery by Elvidge et al. (Elvidge et al., 2004) indicates that a lighted area linearly overestimates a built-up area by approximately a factor of 2. In units of equivalent diameter this translates to an overestimation by a factor of 1.4.

Stable lights provide a valuable complement to census-derived proxies for human settlement patterns. The median area of the 60 080 contiguous lighted settlements in the 1994/95 dataset is 33 km, which corresponds to a median settlement diameter of 6.5 km (circular equivalent). In comparison to the population-weighted median area of 961 km and equivalent resolution of 31 km

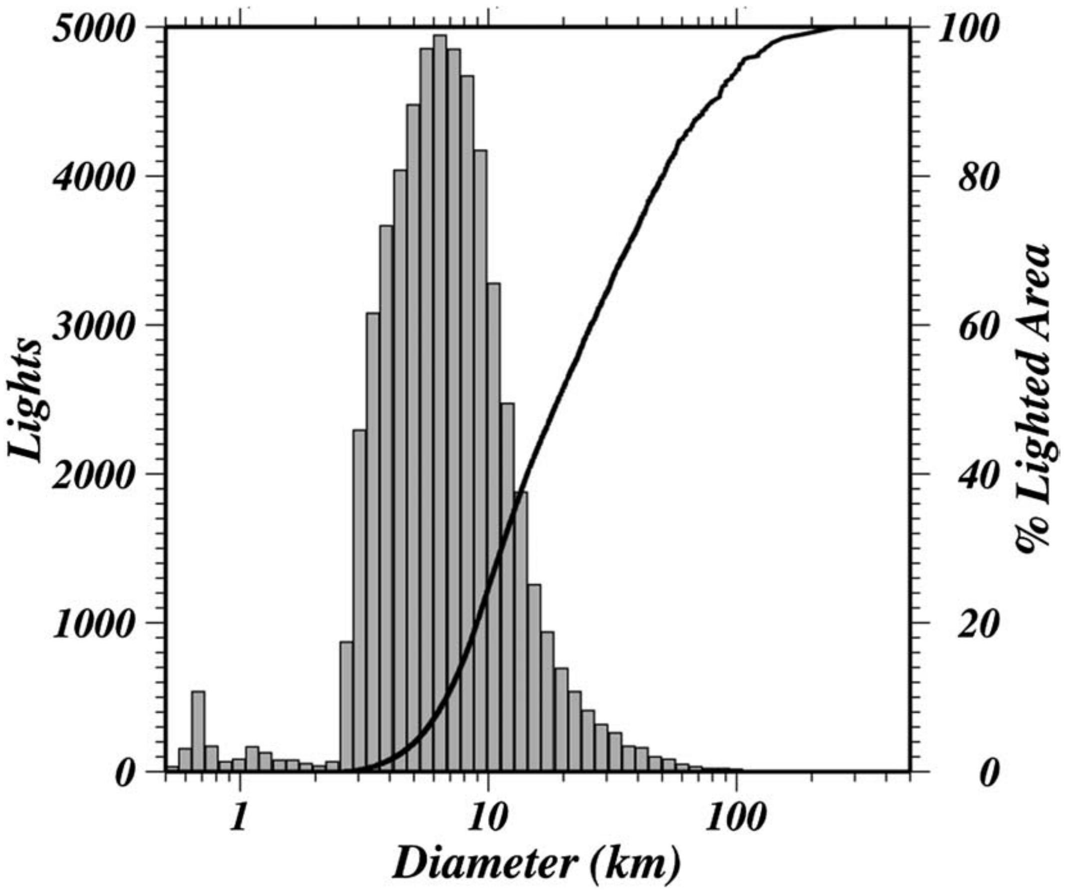

Figure 4. Size and area distributions of lighted settlements circa 1994/95. Number (histogram) and cumulative area (curve) of stable lights from Elvidge et al. (Elvidge et al., 1997a) are plotted as functions of equivalent circular diameter ($2\sqrt{(\text{area}/\pi)}$). While most (83%) lighted settlements are less than 10-km-equivalent diameter, more than 50% of lighted area is associated with the 5% of settlements larger than 20 km.

for the census tracts used in GPW2, the night light dataset offers considerably higher spatial resolution and therefore provides complementary estimates of the number and size of urban settlements. A lighted area is moderately correlated ($r^2 = 0.68$) with population (Sutton et al., 1997; Sutton et al., 2001). Because of the considerable variability in the relationship between a lighted area and population, no conclusions are drawn about the number of people living within specific lighted areas. Rather, the size and location of the lighted settlements are used as spatially explicit indicators of local concentrations of population, which are associated with urban land use.

The area and size distribution of light sources provides a measure of spatial clustering of urban land use. The size distribution of the lighted areas indicates the prevalence of large conurbations relative to the more numerous smaller settlements. Less than 5% of the 60 080 light polygons (circumscribing the contiguous lighted areas) have circular equivalent diameters larger than 20 km yet they account for 50% of the lighted area (Figure 4). The total lighted area (5.18×10^6 km^2) accounts for less than 4% of the 130 582 040 km^2 of inhabited land area. Adjusting for the spatial overestimation of lighted area suggests that the imaged settlements occupy less than 2% of the enumerated land area. This number and the estimate that 50% of the global population occupies less than 3% of the land area support the assertion that nearly half of the world's population lives in urban areas (United Nations, 2001). If a lighted area is used as a proxy for urban area, then satellite data indicate that at least 2.5 million km^2 are occupied by urban and developed areas (including airports, oil production facilities, and other sparsely populated lighted areas). This is certainly an underestimate because of the detection threshold of the OLS sensor (Elvidge et al., 2004), and the fact that many small settlements are not detected or even illuminated at night. Accounting for undetected smaller (and less brightly lit) settlements would increase this area, but without knowing the size frequency distribution of undetected settlements, it is not possible to make a meaningful estimate. The size frequency distribution of lighted settlements does, however, provide a reasonably accurate description of the scaling properties of larger human settlements. In the context of this analysis, the combination of lighted settlements and moderate-resolution census data can distinguish between densely populated rural areas and more heavily developed centers of economic activity.

3. Continental physiography

The physical landscape is generally assumed to be a determinant of urban development. Cultural, political, and socioeconomic factors are also determinants. Global analyses may reveal consistencies that transcend the other nonphysical factors. In the context of this discussion, continental physiography refers to the basic morphologic properties of the landscape. Here we consider elevation above sea level and proximity to permanent rivers and seacoasts. Landscape is also characterized by morphologic properties such as slope and aspect. These properties are strongly scale dependent. A global, scale-based analysis of higher-order morphologic properties is constrained by the accuracy and resolution of global elevation and is beyond the scope of this study. In many areas, the spatial resolution of the census data is not sufficient to support a scale-based analysis. Nonetheless, these properties may be as important as the basic properties considered here. The population and land area relationships summarized here are derived from the more detailed analysis given in Cohen and Small (Cohen and Small, 1998) and Small and Cohen (Small and Cohen, 2004). The analysis presented here extends the previous study by including lighted urban areas.

Coastal proximity is calculated as the horizontal distance to the nearest coastline at each point for which a population estimate is available. The coastline used in the analysis is the Global Self-consistent Hierarchical High Resolution Shoreline (GSHHS) digital coastline file (Wessel and Smith, 1996), which consists of 10 390 243 points worldwide. This product was assembled from the World Vector Shoreline (WVS) and the CIA World Data Bank II datasets (available online at http://www.ngdc.noaa.gov/seg/eco/cdroms/gedii_b/datasets/b14/mw.htm). The largest uncertainty with the coastline data is the definition of the coastline up rivers and estuaries. Elevation is calculated as the vertical distance to mean sea level at each point for which a population estimate was available. Elevation estimates are derived from global, 30 arc sec (30") gridded elevations provided by the United States Geological Survey (USGS) Earth Resources Observation Systems (EROS) Data Center [see online at http://edcwww.cr.usgs.gov/landdaac/landdaac.html]. The 30" elevation model was derived from Defense Mapping Agency (DMA, 1986) map products and DMA digital terrain elevation data (DTED). The vertical uncertainty in the original 30" elevation model is generally in excess of one vertical meter but varies within the dataset as a result of the diversity of sources of the elevation data (Danko, 1992). Fluvial proximity was calculated as the distance from the nearest permanent river as defined by the Digital Chart of the World (available online at http://www.lib.ncsu.edu/stacks/gis/dcw.html). This dataset has limited ability to resolve small tributaries and should not be interpreted as representative of all flowing water sources. The accuracy and resolution of the coastline, elevation, and population data impose important constraints on the conclusions that can be drawn from these global datasets. Calculating each of these parameters (i.e., elevation, coastal proximity, fluvial proximity) for each gridded population estimate results in distributions of population and land area as functions of each parameter. A detailed discussion of this analysis and its results is given in Small and Cohen (Small and Cohen, 1999; Small and Cohen, 2004). (Maps of the physiographic parameters are available online at www.LDEO.columbia.edu/~small/population.html.)

Human population and lighted urban areas are strongly localized with respect to the physiographic parameters considered here. Figure 5 indicates that both population and lighted settlements occur in greatest abundance at low elevations in close proximity to rivers and seacoasts and that all diminish rapidly with distance. In part, this is a consequence of the distribution of available land area. Nonetheless, when population at a given distance (or elevation) is normalized by the available land area at that distance (or elevation), the resulting average population densities still show considerable clustering within 100 km of rivers and seacoasts and within 100 m of sea level (Figure 5). This localization is even more pronounced for lighted settlements as indicated by significant increases in the percentage of lighted area at the smallest elevations and proximities. Together, the area-normalized distributions of population and lighted area suggest that the high average population densities near seacoasts and permanent rivers are primarily urban populations and that the moderate densities at low inland elevations are rural agrarian populations. This is confirmed by the high densities and sparse lighting of major delta systems and river valleys (e.g., Indus, Ganges-Brahmaputra, Mekong, Pearl, Huang-He). The peak in the lighted fraction at low (<50 km) fluvial proximity contrasts the more gradual decrease in the average population density, further highlighting the distinction between urban and rural populations relative to permanent rivers. Average population densities have maxima corresponding to the same peaks observed in the distributions of population and lighted area, but they also highlight other peaks not apparent in the other distributions. The peak in average density at the 2300-m elevation corresponds to the densely populated

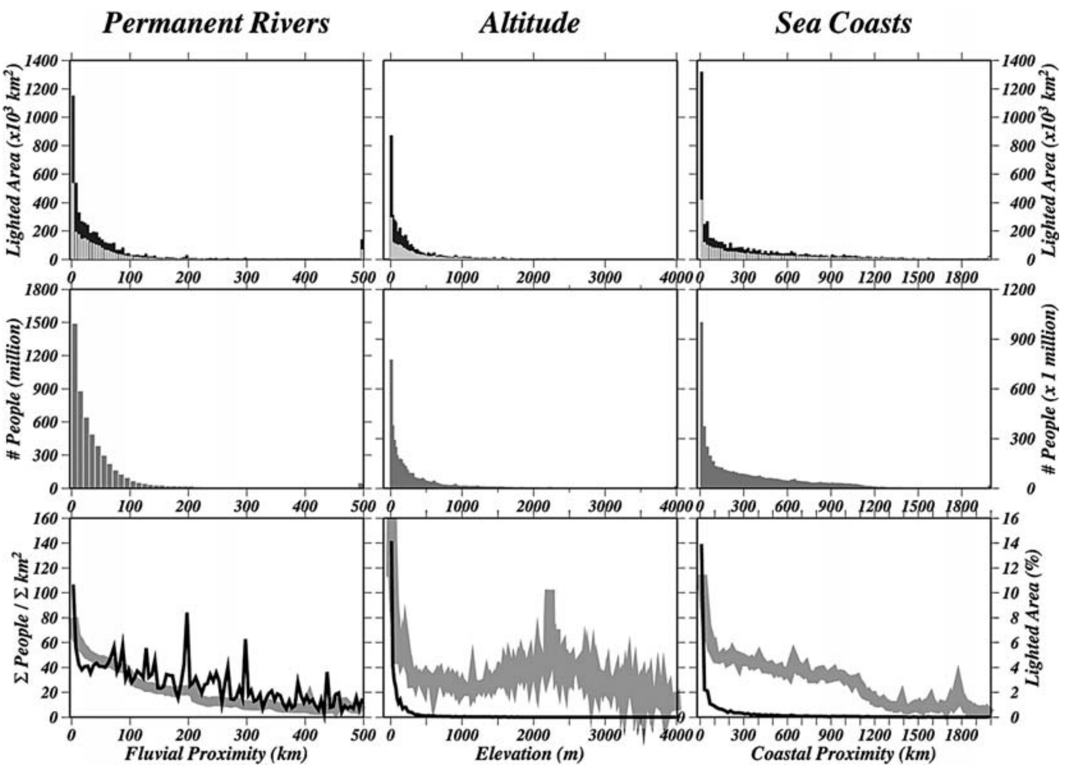

Figure 5. Distributions of lighted area and population as functions of continental physiographic parameters. (top row) The lighted area is strongly localized with the both lighted settlements smaller than 20-km diameter (lighter) and total lighted area (darker) diminishing rapidly with elevation and distance from rivers and seacoasts. (middle row) The total population shows a similar localization. In part, this is a result of the distribution of available land area at each distance and elevation, but (bottom row) when population at each distance (or elevation) is normalized by the available area, the resultant average population densities still show strong localization within 100 km of seacoasts and rivers and within 100 m of sea level. The lighted fraction of land area diminishes even more rapidly. Details of the population and land area analysis are given in Small and Cohen (Small and Cohen, 2004).

Mexican plateau. Although the density approaches the high values occurring at the lowest elevations, this peak represents far fewer people (518 million versus 4.8 million).

4. Climate

In addition to landscape, climatic factors are often assumed to influence human habitation patterns at continental scales. As with landscape, these assumptions are rarely quantified. This analysis considers basic properties of temperature and precipitation in the form of annual averages and annual ranges of each. As with landscape, climate is also characterized by scale-dependent properties. Climatic variables have the added complexity of temporal variability across a wide range of scales. Many of these properties can be represented in terms of the covariation of the phase and amplitude of the temperature and precipitation cycles. A thorough analysis of these higher-order climate parameters is beyond the scope of this study, but these parameters may be as important as the first order considered here. The multidimensional analysis described by Small and Cohen (Small and Cohen, 1999; Small and Cohen, 2004) could be extended to include these dimensions as well as the higher-order physiographic parameters discussed previously. The population and land area relationships summarized here are derived from the more detailed analysis given in Small and Cohen (Small and Cohen, 2004).

Climatic parameters were derived from global climatologies compiled by New et al. (New et al., 1999; New et al., 2000). Gridded monthly averages of 12 092 temperature and 19 295 precipitation stations, compiled over the years 1961–90, were used to calculate annual average and annual range (maximum minus minimum) for each 0.5° grid cell provided by New et al. (New et al., 1999; New et al., 2000). The annual averages and ranges quantify and discriminate the primary climatic divisions observed at global scales. These climatic data do not resolve distinct microclimates that may exist at scales finer than 0.5° (about 55 km at the equator). Other important climatic variables (e.g., wind, frost days, cloud cover, potential evapotranspiration) are not resolved by these data. A detailed discussion of this analysis and its results is given in Small and Cohen (Small and Cohen, 1999; Small and Cohen, 2004). (Maps of the climatic parameters are available online at www.LDEO.columbia.edu/~small/population.html.)

The distributions of population and lighted settlements are not strongly localized with respect to any of the climatic parameters considered here. While all of the distributions have peaks (Figure 6), none are as strongly skewed as any of the physiographic parameters (Figure 5). Even when land area distributions are considered, the average population densities are not as strongly localized as those for physiographic parameters. The distributions of lighted area and population differ markedly for average temperature and annual variability of precipitation. These differences of distribution highlight distinctions between urban and rural population and development. The large peak in population at annual average temperatures of 25°–26°C is not reflected in a comparable peak in the lighted area. Similarly, the broad secondary peak in population at annual precipitation ranges of 2000 mm yr^{-1} is not accompanied by a similar peak in the lighted area. The causes and implications of these differences are discussed below.

Superimposing lighted and inhabited land area distributions in a two-dimensional climatic parameter space shows the extent to which different biomes are subject to urban land use. In this example, the parameter space is spanned by mean annual temperature and mean annual precipitation. Figure 7 shows the distribution of all land areas included in census enumerations as darker than the background gray. This corresponds to almost all of Earth's ice-free land area and can be interpreted as a proxy for potentially habitable (at some density) land distribution. Superimposed on the land area distribution is the distribution of lighted settlements (lighter than background gray). The combination of

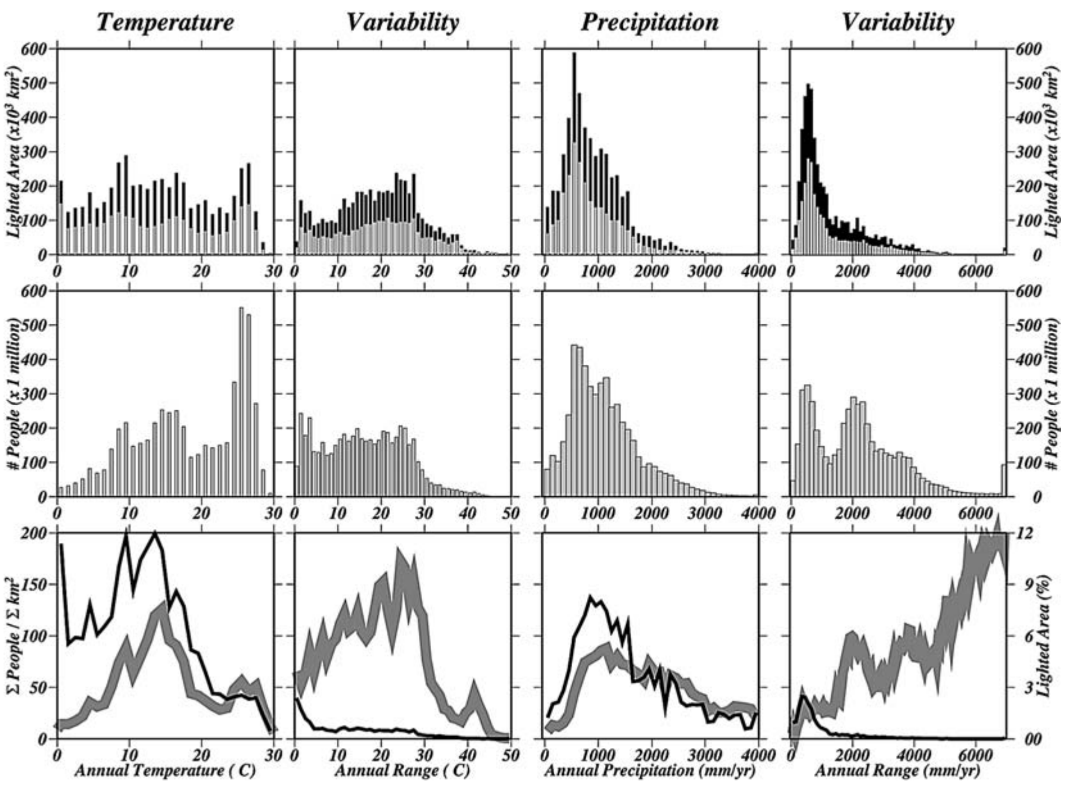

Figure 6. Distributions of population, inhabited land area, and lighted area as functions of climatic parameters. (top row) Lighted area and (middle row) population have similar distributions with notable exceptions at 26°C of annual average temperature and 2000 mm yr^{-1} of annual precipitation range. (bottom row) Average population densities and lighted fractions of land area are much less localized than those of the physiograhic distributions shown in Figure 5. The densities highlight patterns not obvious in the distributions alone. Details of the population and land area analysis are given in Small and Cohen (Small and Cohen, 2004).

distributions highlights the most densely urbanized regions of the climatic parameter space. Although individual settlements span almost the entire range of available land areas, most of the urbanized land area is concentrated in a large temperate mode and a smaller tropical mode. A simplified schematic distribution of biomes is shown for the temperature/precipitation parameter space. This schematic diagram does not account for the important effects of the seasonal phase of temperature and precipitation cycles, soil properties, and other factors that influence the distribution of biomes.

5. Discussion

The modern human habitat can be quantified as distributions of population density and lighted area within geophysical parameter spaces. Conventional maps of

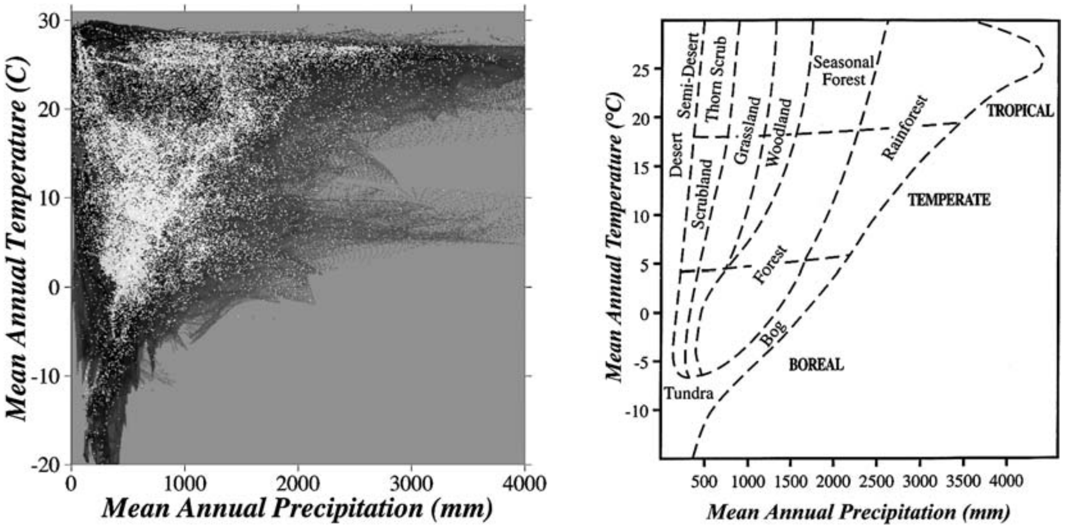

Figure 7. Distributions of land area and urban land use in major biomes. (left) A bivariate histogram shows enumerated land area (darker than background) and urban land use (lighter than background) in a climatic parameter space. Darker regions correspond to sparsely urbanized areas. Lighter regions correspond to centroids of individual lighted settlements. (right) The generalized distribution of major biomes (modified from Houghton et al., 1996) indicates that some lighted settlements occur in all biomes, but that the midrange of the temperate biome is the most extensively urbanized. Note the distinct cluster of settlements spanning the tropical biomes.

population distribution clearly show the distinction between sparsely and densely inhabited regions at global scales but do not clearly convey the magnitude of spatial clustering within the inhabited regions. Quantitative analysis of gridded census data reveals the extent and location of high population densities in both geographic space and in geophysical parameter spaces. Distributions in geophysical parameter spaces can reveal patterns that are not obvious in geographic space. Large variations in population density are important because they correspond to very different land-use patterns and ecological impacts. Using night lights as a proxy for urban land use significantly increases the spatial resolution of the analysis so that urban population distributions can be considered in the context of the physical landscape.

Spatial localization with respect to continental physiography indicates a strong correspondence between physical landscape and urban development. Average population densities diminish rapidly with elevation and distance from seacoasts and permanent rivers but maintain rural densities over much larger ranges of each parameter. Stronger localization of lighted areas coincident with the highest average densities highlights the distinction between urban and rural populations. Area-normalized distributions of lighted area and population indicate that urban land use is areally insignificant at higher elevations (>500 m) farther from seacoasts (>500 km), while rural densities extend as far as 1200 km inland and 3600 m above sea level. The geographic localization of urban land use quantifies the recognized importance of navigable water to economic development (Smith, 1776; Sachs, 1997; Gallup and Sachs, 1999). It is, however, important to acknowledge the fact that many other environmental factors influence human habitation, and the simple analysis presented here does not provide a complete explanation of population distribution.

Physical landscape also influences agricultural land use, but the spatial localization is not as pronounced as with urban land use. To some extent, this is a consequence of the fact that agriculture requires more space per person (fed) than habitation. Nonetheless, at a global scale, urban land use is extremely localized within the areas inhabited by humans. Traditional agricultural practices have also adapted to a wide range of climatic and physiographic environments. Most notably, topographic slope and access to navigable water pose less of an obstacle to traditional agricultural land use than to urban land use. Ironically, increasing mechanization of agricultural practice may reduce the range of physical environments suitable for intensive, modern agricultural land use relative to traditional lower-intensity agricultural practices (e.g., terracing in mountainous terrain).

Human population is not strongly localized with respect to the basic climatic parameters considered here. While the global population distribution is relatively sparse in some climatic zones and biomes (e.g., tundra, high-altitude desert, tropical rain forest), the distributions are far more uniform with respect to climatic parameters than with respect to physiographic parameters. There are, however, some interesting examples of high average densities within the climatic parameter space. Specifically, the high densities at high values of the annual precipitation range correspond to regions receiving the Asian monsoon. Urban land cover is somewhat localized at low annual ranges of temperature and precipitation, but the localization is not as pronounced as with the physiographic parameters. The implication is that adaptation to climate has allowed expansion of the human habitat while spatial clustering with respect to the physical landscape currently results in a simultaneous concentration of population within the expanding habitat.

Considered together, temporal projections of population growth and the current spatial distribution of population and urban land use have implications for human impact on ecosystems. Specifically, the clustering of urban areas of all sizes near rivers and seacoasts suggests that riparian and coastal ecosystems are most directly impacted by urban land use. As current settlements are likely to evolve into larger urban areas, these regions are likely to be increasingly impacted as demographic momentum and urban migration accelerate and focus future population growth. Rural to urban migration will increase urban populations (and presumably land use), but it will not necessarily diminish agricultural land-use impacts because most existing agricultural regions are likely to remain under cultivation as large-scale mechanized cultivation replaces smaller-scale agricultural land use. The current spatial distribution of urban land use can also provide boundary conditions for future scenarios and projections of urban growth. Mapping present and future (projected) urban land-use distributions in geophysical parameter spaces could serve the dual purpose of 1) providing geophysical constraints for process models with physical parameters, and 2) interpreting the impact of increasing urban land use on specific ecosystems. If population growth models limit future habitation to the current range of physical environments, then potential future habitat could be constrained by combinations of geophysical parameters. Conversely, if growth models predict future habitation on the basis of socioeconomic factors, the potentially impacted ecosystems could be anticipated on the basis of the geophysical parameters of the corresponding geographic areas. As more spatial data become available, the methodology used here could be extended to high-dimensional analyses of physical and socioeconomic parameters and their interactions. This is discussed in greater detail by Small and Cohen (Small and Cohen, 2004).

Increasing urbanization of the global population may be inevitable, but it is not necessarily negative. Urban settlements provide economies of scale that can allow for a more efficient use of resources relative to dispersed rural and suburban populations. Similarly, human impact on ecosystems may, in theory, be more easily regulated in smaller urban areas than in dispersed rural settlements. Anticipating the location and potential impacts of future urban land use could facilitate mediation of unintended negative consequences of population growth. Understanding the systematics of the current population distribution is a prerequisite for accurate predictions and scenarios.

Acknowledgments. This work was funded by the UCAR Climate and Global Change Research Program, the Doherty Foundation, and the NASA Socioeconomic Data and Applications Center (SEDAC) at CIESIN, Columbia University. The author would like to thank Deborah Balk, Bob Chen, Joel Cohen, Uwe Deichman, Chris Elvidge, Francesca Pozzi, and Greg Yetman for helpful suggestions, insights, and discussions.

References

Berry, B.L., 1990: Urbanization, in *The Earth as Transformed by Human Action*, edited by B.L. Turner et al., Cambridge University Press, Cambridge, 103–119.

Bornstein, R., and G.M. LeRoy, 1990: Urban barrier effects on convective and frontal thunderstorms, paper presented at the Fourth Conference on Mesoscale Processes, Am. Meteor. Soc., Boulder, CO, 25–29 June, 120–121.

Bornstein, R., and Q.L. Lin, 2000: Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmos. Environ.,* **34,** 507–516.

Chameides, W.L., P.S. Kasibhatla, J. Yienger, and H.H. Levy, 1994: Growth of continental scale metro-agro-plexes, regional ozone pollution and world food production. *Science,* **264,** 74–75.

CIESIN, cited 2000: Gridded Population of the World (GPW), Version 2. CIESIN, Columbia University, New York. [Available online at http://sedac.ciesin.columbia.edu/plue/gpw/index.html.]

Cincotta, R.P., J. Wisnewski, and R. Engelman, 2000: Human population in the biodiversity hotspots. *Nature,* **404,** 990–992.

Cohen, J.E., and C. Small, 1998: Hypsographic demography: The global distribution of population with altitude. *Proc. Natl. Acad. Sci.,* **95,** 1–6.

Croft, T.A., 1978: Nighttime images of the earth from space. *Sci. Am.,* **239,** 68–79.

Danko, D.M., 1992: The digital chart of the world. *GeoInfo Syst.,* **2,** 29–36.

Deichmann, U., D. Balk, and G. Yetman, 2001: Transforming population data for interdisciplinary usages: From census to grid. CIESIN manuscript, in press. [Available online at http://sedac.ciesin.columbia.edu/plue/gpw/GPWdocumentation.pdf.]

DMA, 1986: Defense Mapping Agency product specifications for digital terrain elevation data (DTED). 2d ed. Defense Mapping Agency Aerospace Center, St. Louis, Missouri.

Elvidge, C.D., K.E. Baugh, E.A. Kihn, H.W. Kroehl, and E.R. Davis, 1997a: Mapping city lights with nighttime data from the DMSP operational linescan system. *Photogramm. Eng. Remote Sens.,* **63** (6), 727–734.

Elvidge, C.D., K.E. Baugh, E.A. Kihn, H.W. Kroehl, E.R. Davis, and C.W. Davis, 1997b: Relation between satellite observed visible-near infrared emissions, population, economic activity and electric power consumption. *Int. J. Remote Sens.,* **18,** 1373–1379.

Elvidge, C.D., K.E. Baugh, J.B. Diez, T. Bland, P.C. Sutton, and H.W. Kroehl, 1999: Radiance calibration of DMSP-OLS low-light imaging data of human settlements. *Remote Sens. Environ.,* **68,** 77–88.

Elvidge, C.D., J. Safran, I.L. Nelson, B.T. Tuttle, V.R. Hobson, and K.E. Baugh, 2004: Area and positional accuracy of DMSP nighttime lights data, in *Remote Sensing and GIS Accuracy Assessment,* edited by R. Lunetta and J.G. Lyon, CRC Press, in press.

Gallup, J.L., and J.D. Sachs, 1999: Geography and economic development. *Int. Reg. Sci. Rev.,* **22,** 179–232.

Hassan, F.A., 1981: *Demographic Archaeology*. Academic Press, New York, 289 pp.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds., 1996: *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, 572 pp.

Landsberg, H.E., 1981: *The Urban Climate*. Academic Press, New York, 275 pp.

Li, B., and R. Avissar, 1994: The impact of spatial variability of land-surface characteristics on land-surface heat fluxes. *J. Clim.,* **7,** 527–537.

Meyer, W.B., and B.L. Turner II, 1992: Human population growth and global land-use/cover change. *Annu. Rev. Ecol. Syst.,* **23,** 39–61.

New, M.G., M. Hulme, and P.D. Jones, 1999: Representing twentieth-century space–time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. *J. Clim.,* **12,** 829–856.

New, M.G., M. Hulme, and P.D. Jones, 2000: Representing twentieth-century space–time climate variability. Part II: Development of a 1901–96 monthly terrestrial climate field. *J. Clim.,* **13,** 2217–2238.

O'Neill, B., and D. Balk, 2001: Projecting world population futures. *Pop. Bull.,* **56**(3), 1–40.

Pielke, R.A., Sr., G. Marland, R.A. Betts, T.N. Chase, J.L. Eastman, J.O. Niles, D. Niyogi, and S.W. Running, 2002: The influence of land-use change and landscape dynamics on the climate system—Relevance to climate change policy beyond the radiative effect of greenhouse gases. *Philos. Trans. Roy. Soc. London,* **360A,** 1705–1719.

Roy, S., and R. Avissar, 2000: Scales of response of the convective boundary layer to land-surface heterogeneity. *Geophys. Res. Lett.,* **27,** 533–536.

Sachs, J., 1997: The limits of convergence: Nature, nurture and growth. *The Economist*, 14 June, 19–22.

Small, C., and J.E. Cohen, 1999: Continental physiography, climate and the global distribution of human population, paper presented at the International Symposium on Digital Earth, Chinese Academy of Sciences, Beijing, China, 965–971. [Available online at www.LDEO.Columbia.edu/~small/population.html.]

Small, C., and J.E. Cohen, 2004: Continental physiography, climate and the global distribution of human population. *Curr. Anthropol.,* **45,** 269–277.

Small, C., F. Pozzi, and C. Elvidge, 2004: Mapping urban areas with night lights and Landsat imagery. *Photogramm. Eng. Remote Sens.,* submitted.

Smith, A., 1776: *An Inquiry into the Nature and Causes of the Wealth of Nations*. Reprint 1937, edited by Edwin Cannan, Modern Library, New York, 718 pp.

Sutton, P., C. Roberts, C. Elvidge, and H. Meij, 1997: A comparison of nighttime satellite imagery and population density for the continental United States. *Photogramm. Eng. Remote Sens.,* **63,** 1303–1313.

Sutton, P., D. Roberts, C. Elvidge, and K. Baugh, 2001: Census from heaven: An estimate of the global human population using night-time satellite imagery. *Int. J. Remote Sens.,* **22,** 3061–3076.

Tobler, W., U. Deichmann, J. Gottsegen, and K. Maloy, 1997: World population in a grid of spherical quadrilaterals. *Int. J. Population Geogr.,* **3,** 203–225.

Turner, B.L.I., W.C. Clark, R.W. Kates, J.F. Richards, J.T. Mathews, and W.B. Meyer, 1990: *The Earth as Transformed by Human Action*. Cambridge University Press, Cambridge, 713 pp.

United Nations, 2001: World Urbanization Prospects: The 2001 Revision. United Nations, *(ST/ESA/SER.A/166), Sales No. E.97.XIII.3*. [Available online at http://www.un.org/esa/population/publications/wup2001/WUP2001report.htm.]

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo, 1997: Human domination of Earth's ecosystems. *Science,* **277,** 494–499.

Wessel, P., and W.H.F. Smith, 1996: A global self-consistent, hierarchical, high-resolution shoreline database. *J. Geophys. Res.,* **101,** 8741–8743.