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Putting people in the map: anthropogenic biomes of the world

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Putting people in the map: anthropogenic biomes of the world

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Humans have fundamentally altered global patterns of biodiversity and ecosystem processes. Surprisingly, existing systems for representing these global patterns, including biome classifications, either ignore humans altogether or simplify human influence into, at most, four categories. Here, we present the first characterization of terrestrial biomes based on global patterns of sustained, direct human interaction with ecosystems. Eighteen "anthropogenic biomes" were identified through empirical analysis of global population, land use, and land cover. More than 75% of Earth's ice-free land showed evidence of alteration as a result of human residence and land use, with less than a quarter remaining as wildlands, supporting just 11% of terrestrial net primary production. Anthropogenic biomes offer a new way forward by acknowledging human influence on global ecosystems and moving us toward models and investigations of the terrestrial biosphere that integrate human and ecological systems.

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Humans have long distinguished themselves from other species by shaping ecosystem form and process using tools and technologies, such as fire, that are beyond the capacity of other organisms (Smith 2007). This exceptional ability for ecosystem engineering has helped to sustain unprecedented human population growth over the past half century, to such an extent that humans now consume about one-third of all terrestrial net primary production (NPP; Vitousek *et al*. 1986; Imhoff *et al*. 2004) and move more earth and produce more reactive nitrogen than all other terrestrial processes combined (Galloway 2005; Wilkinson and McElroy 2007). Humans are also causing global extinctions (Novacek and Cleland 2001) and changes in climate that are comparable to any observed in the natural record (Ruddiman 2003; IPCC 2007). Clearly, *Homo sapiens* has emerged as a force of nature rivaling climatic and geologic forces in shaping the terrestrial biosphere and its processes.

In a nutshell:

- Anthropogenic biomes offer a new view of the terrestrial biosphere in its contemporary, human-altered form
- Most of the terrestrial biosphere has been altered by human residence and agriculture
- Less than a quarter of Earth's ice-free land is wild; only 20% of this is forests and > 36% is barren
- More than 80% of all people live in densely populated urban and village biomes
- Agricultural villages are the most extensive of all densely populated biomes and one in four people lives in them

Biomes are the most basic units that ecologists use to describe global patterns of ecosystem form, process, and biodiversity. Historically, biomes have been identified and mapped based on general differences in vegetation type associated with regional variations in climate (Udvardy 1975; Matthews 1983; Prentice *et al*. 1992; Olson *et al*. 2001; Bailey 2004). Now that humans have restructured the terrestrial biosphere for agriculture, forestry, and other uses, global patterns of species composition and abundance, primary productivity, land-surface hydrology, and the biogeochemical cycles of carbon, nitrogen, and phosphorus, have all been substantially altered (Matson *et al*. 1997; Vitousek *et al*. 1997; Foley *et al*. 2005). Indeed, recent studies indicate that human-dominated ecosystems now cover more of Earth's land surface than do "wild" ecosystems (McCloskey and Spalding 1989; Vitousek *et al*. 1997; Sanderson *et al*. 2002, Mittermeier *et al*. 2003; Foley *et al*. 2005).

It is therefore surprising that existing descriptions of biome systems either ignore human influence altogether or describe it using at most four anthropogenic ecosystem classes (urban/built-up, cropland, and one or two cropland/natural vegetation mosaic(s); classification systems include IGBP, Loveland *et al*. 2000; "Olson Biomes", Olson *et al*. 2001; GLC 2000, Bartholome and Belward 2005; and GLOBCOVER, Defourny *et al*. 2006). Here, we present an alternate view of the terrestrial biosphere, based on an empirical analysis of global patterns of sustained direct human interaction with ecosystems, yielding a global map of "anthropogenic biomes". We then examine the potential of anthropogenic biomes to serve as a new global framework for ecology, complete with

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testable hypotheses, that can advance research, education, and conservation of the terrestrial biosphere as it exists today – the product of intensive reshaping by direct interactions with humans.

Human interactions with ecosystems

Human interactions with ecosystems are inherently dynamic and complex (Folke *et al.* 1996; DeFries *et al.* 2004; Rindfuss *et al.* 2004); any categorization of these is a gross oversimplification. Yet there is little hope of understanding and modeling these interactions at a global scale without such simplification. Most global models of primary productivity, species diversity, and even climate depend on stratifying the terrestrial surface into a limited number of functional types, land-cover types, biomes, or vegetation classes (Haxeltine and Prentice 1996; Thomas *et al.* 2004; Feddema *et al.* 2005).

Human interactions with ecosystems range from the relatively light impacts of mobile bands of hunter-gatherers to the complete replacement of pre-existing ecosystems with built structures (Smil 1991). Population density is a useful indicator of the form and intensity of these interactions, as increasing populations have long been considered both a cause and a consequence of ecosystem modification to produce food and other necessities (Boserup 1965, 1981; Smil 1991; Netting 1993). Indeed, most basic historical forms of human–ecosystem interaction are associated with major differences in population density, including foraging (< 1 person km^{-2}), shifting (> 10 persons km^{-2}), and continuous cultivation (> 100 persons km^{-2}); populations denser than 2500 persons km^{-2} are believed to be unsupportable by traditional subsistence agriculture (Smil 1991; Netting 1993).

In recent decades, industrial agriculture and modern transportation have created new forms of human–ecosystem interaction across the full range of population densities, from low-density exurban developments to vast conurbations that combine high-density cities, low-density suburbs, agriculture, and even forested areas (Smil 1991; Qadeer 2000; Theobald 2004). Nevertheless, population density can still serve as a useful indicator of the form and intensity of human–ecosystem interactions within a specific locale, especially when populations differ by an order of magnitude or more. Such major differences in population density help to distinguish situations in which humans may be considered merely agents of ecosystem transformation (ecosystem engineers), from situations in which human populations have grown dense enough that their local resource consumption and waste production form a substantial component of local biogeochemical cycles and other ecosystem processes. To begin our analysis, we therefore categorize human–ecosystem interactions into four classes, based on major differences in population density: high population intensity ("dense", >100 persons km^{-2}), substantial population intensity ("residential", 10 to 100 persons km^{-2}), minor population ("populated", 1 to 10 persons km^{-2}), and inconsequential population ("remote", < 1 person km^{-2}). Population class names are defined only in the context of this study.

Identifying anthropogenic biomes: an empirical approach

We identified and mapped anthropogenic biomes using the multi-stage empirical procedure detailed in WebPanel 1 and outlined below, based on global data for *population* (urban, non-urban), *land use* (percent area of pasture, crops, irrigation, rice, urban land), and *land cover* (percent area of trees and bare earth); data for NPP, IGBP land cover, and Olson biomes were obtained for later analysis (WebPanel 1 includes references for all data sources). Biome analysis was conducted at 5 arc minute resolution (5' grid cells cover ~ 86 km^2 at the equator), a spatial resolution selected as the finest allowing direct use of high-quality land-use area estimates. First, "anthropogenic" 5' cells were separated from "wild" cells, based on the presence of human populations, crops, or pastures. Anthropogenic cells were then stratified into the population density classes described above ("dense", "residential", "populated", and "remote"), based on the density of their non-urban population. We then used cluster analysis, a statistical procedure designed to identify an optimal number of distinct natural groupings (clusters) within a dataset (using SPSS 15.01), to identify natural groupings within the cells of each population density class and within the wild class, based on non-urban population density and percent urban area, pasture, crops, irrigated, rice, trees, and bare earth. Finally, the strata derived above were described, labeled, and organized into broad logical groupings, based on their populations, land-use and land-cover characteristics, and their regional distribution, yielding the 18 anthropogenic biome classes and three wild biome classes illustrated in Figure 1 and described in Table 1. (WebTables 1 and 2 provide more detailed statistics; WebPanel 2 provides maps viewable in Google Earth, Google Maps, and Microsoft Virtual Earth, a printable wall map, and map data in GIS format.)

A tour of the anthropogenic biomes

When viewed globally, anthropogenic biomes clearly dominate the terrestrial biosphere, covering more than three-quarters of Earth's ice-free land and incorporating nearly 90% of terrestrial NPP and 80% of global tree cover (Figures 1 and 2a; WebTable 2). About half of terrestrial NPP and land were present in the forested and rangeland biomes, which have relatively low population densities and potentially low impacts from land use (excluding residential rangelands; Figures 1 and 2a). However, one-third of Earth's ice-free land and about 45% of terrestrial NPP occurred within cultivated and substantially populated biomes (dense settlements, villages, croplands, and residential rangelands; Figures 1 and 2a).

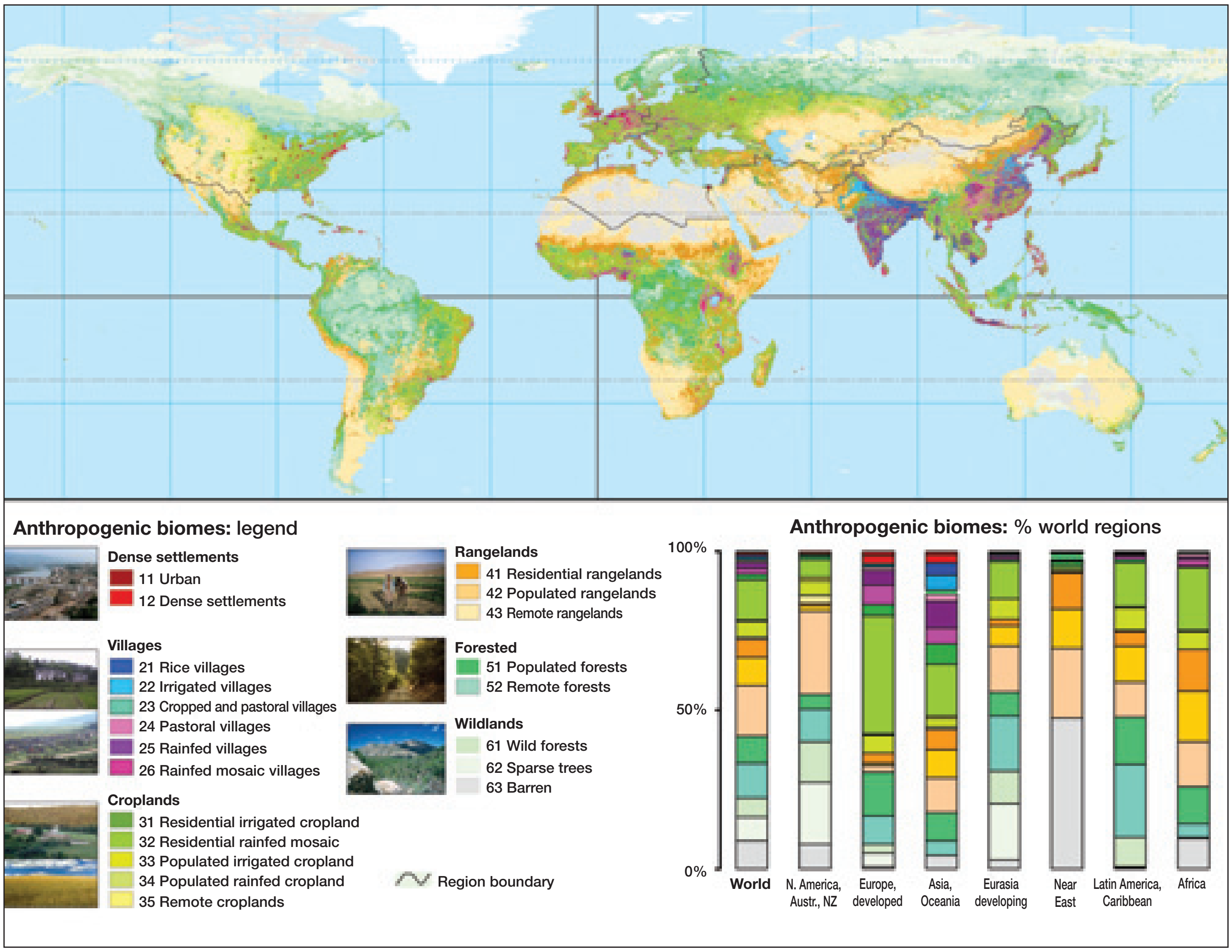

Figure 1. *Anthropogenic biomes: world map and regional areas. Biomes are organized into groups (Table 1), and sorted in order of population density. Map scale = 1:160 000 000, Plate Carrée projection (geographic), 5 arc minute resolution (5' = 0.0833°). Regional biome areas are detailed in WebTable 3; WebPanel 2 provides interactive versions of this map.*

Of Earth's 6.4 billion human inhabitants, 40% live in dense settlements biomes (82% urban population), 40% live in village biomes (38% urban), 15% live in cropland biomes (7% urban), and 5% live in rangeland biomes (5% urban; forested biomes had 0.6% of global population; Figure 2a). Though most people live in dense settlements and villages, these cover just 7% of Earth's ice-free land, and about 60% of this population is urban, living in the cities and towns embedded within these biomes, which also include almost all of the land we have classified as urban (94% of 0.5 million km^2, although this is probably a substantial underestimate; Salvatore *et al.* 2005; Figure 2a).

Village biomes, representing dense agricultural populations, were by far the most extensive of the densely populated biomes, covering 7.7 million km^2, compared with 1.5 million km^2 for the urban and dense settlements biomes. Moreover, village biomes house about one-half of the world's non-urban population (1.6 of ~3.2 billion persons). Though about one-third of global urban area is also embedded within these biomes, urban areas accounted for just 2% of their total extent, while agricultural land (crops and pasture) averaged > 60% of their area. More than 39% of densely populated biomes were located in Asia, which also incorporated more than 60% of that continent's total global area, even though this region was the fifth largest of seven regions (Figure 1; WebTable 3). Village biomes were most common in Asia, where they covered more than a quarter of all land. Africa was second, with 13% of village biome area, though these covered just 6% of Africa's land. The most intensive land-use practices were also disproportionately located in the village biomes, including about half the world's irrigated land (1.4 of 2.7 million km^2) and two-thirds of global rice land (1.1 of 1.7 million km^2; Figure 2a).

After rangelands, cropland biomes were the second most extensive of the anthropogenic biomes, covering about 20% of Earth's ice-free land. Far from being simple, crop-covered landscapes, cropland biomes were mostly mosaics of cultivated land mixed with trees and pastures (Figure 3c). As a result, cropland biomes constituted only slightly more than half of the world's total crop-covered

Table 1. Anthropogenic biome descriptions

Group		*Biome*	*Description*
Dense settlements			Dense settlements with substantial urban area
	11	Urban	Dense built environments with very high populations
	12	Dense settlements	Dense mix of rural and urban populations, including both suburbs and villages
Villages			Dense agricultural settlements
	21	Rice villages	Villages dominated by paddy rice
	22	Irrigated villages	Villages dominated by irrigated crops
	23	Cropped and pastoral villages	Villages with a mix of crops and pasture
	24	Pastoral villages	Villages dominated by rangeland
	25	Rainfed villages	Villages dominated by rainfed agriculture
	26	Rainfed mosaic villages	Villages with a mix of trees and crops
Croplands			Annual crops mixed with other land uses and land covers
	31	Residential irrigated cropland	Irrigated cropland with substantial human populations
	32	Residential rainfed mosaic	Mix of trees and rainfed cropland with substantial human populations
	33	Populated irrigated cropland	Irrigated cropland with minor human populations
	34	Populated rainfed cropland	Rainfed cropland with minor human populations
	35	Remote croplands	Cropland with inconsequential human populations
Rangeland			Livestock grazing; minimal crops and forests
	41	Residential rangelands	Rangelands with substantial human populations
	42	Populated rangelands	Rangelands with minor human populations
	43	Remote rangelands	Rangelands with inconsequential human populations
Forested			Forests with human populations and agriculture
	51	Populated forests	Forests with minor human populations
	52	Remote forests	Forests with inconsequential human populations
Wildlands			Land without human populations or agriculture
	61	Wild forests	High tree cover, mostly boreal and tropical forests
	62	Sparse trees	Low tree cover, mostly cold and arid lands
	63	Barren	No tree cover, mostly deserts and frozen land

area (8 of 15 million km^2), with village biomes hosting nearly a quarter and rangeland biomes about 16%. The cropland biomes also included 17% of the world's pasture land, along with a quarter of global tree cover and nearly a third of terrestrial NPP. Most abundant in Africa and Asia, residential, rainfed mosaic was by far the most extensive cropland biome and the second most abundant biome overall (16.7 million km^2), providing a home to nearly 600 million people, 4 million km^2 of crops, and about 20% of the world's tree cover and NPP – a greater share than the entire wild forests biome.

Rangeland biomes were the most extensive, covering nearly a third of global ice-free land and incorporating 73% of global pasture (28 million km^2), but these were found primarily in arid and other low productivity regions with a high percentage of bare earth cover (around 50%; Figure 3c). As a result, rangelands accounted for less than 15% of terrestrial NPP, 6% of global tree cover, and 5% of global population.

Forested biomes covered an area similar to the cropland biomes (25 million km^2 versus 27 million km^2 for croplands), but incorporated a much greater tree-covered area (45% versus 25% of their global area). It is therefore surprising that the total NPP of the forested biomes was nearly the same as that of the cropland biomes (16.4 versus 16.0 billion tons per year). This may be explained by the lower productivity of boreal forests, which predominate in the forested biomes, while cropland biomes were located in some of the world's most productive climates and soils.

Wildlands without evidence of human occupation or land use occupied just 22% of Earth's ice-free land in this analysis. In general, these were located in the least productive regions of the world; more than two-thirds of their area occurred in barren and sparsely tree-covered regions. As a result, even though wildlands contained about 20% cover by wild forests (a mix of boreal and tropical forests; Figure 2c), wildlands as a whole contributed only about 11% of total terrestrial NPP.

Anthropogenic biomes are mosaics

It is clear from the biome descriptions above, from the land-use and land-cover patterns in Figure 3c, and most of all, by comparing our biome map against high-resolution satellite imagery (WebPanel 2), that anthropogenic biomes are best characterized as heterogeneous landscape mosaics, combining a variety of different land uses and land covers. Urban areas are embedded within agricultural areas, trees are interspersed with croplands and housing, and managed vegetation is mixed with semi-natural vegetation (eg croplands are embedded within rangelands and forests). Though some of this heterogeneity might be explained by the relatively coarse resolution of our analysis, we suggest a more basic explanation: that direct interactions between humans and ecosystems generally take place within heterogeneous landscape mosaics (Pickett and Cadenasso 1995; Daily 1999). Further, we propose that this heterogeneity has three causes, two of which are anthropogenic and all of which are fractal in nature (Levin 1992), producing similar patterns across spatial scales ranging from the land holdings of individual households to the global patterning of the anthropogenic biomes.

We hypothesize that even in the most densely populated biomes, most landscape heterogeneity is caused by natural variation in terrain, hydrology, soils, disturbance regimes (eg fire), and climate, as described by conventional models of ecosystems and the terrestrial biosphere (eg Levin 1992; Haxeltine and Prentice 1996; Olson *et* *al*. 2001). Anthropogenic enhancement of natural landscape heterogeneity represents a secondary cause of heterogeneity within anthropogenic biomes, explained in part by the human tendency to seek out and use the most productive lands first and to work and populate these lands most intensively (Huston 1993). At a global scale, this process may explain why wildlands are most common in those parts of the biosphere with the least potential for agriculture (ie polar regions, mountains, low fertility tropical soils; Figure 1) and why, at a given percentage of tree cover, NPP appears higher in anthropogenic biomes with higher population densities (compare NPP with tree cover, especially in wild forests versus forested biomes; Figure 3c). It may also explain why most human populations, both urban and rural, appear to be associated with intensive agriculture (irrigated crops, rice), and not with pasture, forests, or other, less intensive land uses (Figure 3c). Finally, this hypothesis explains why most fertile valleys and floodplains in favorable climates are already in use as croplands, while neighboring hillslopes and mountains are often islands of semi-natural vegetation, left virtually undisturbed by local populations (Huston 1993; Daily 1999). The third cause of landscape heterogeneity in anthropogenic biomes is entirely anthropogenic: humans create landscape heterogeneity directly, as exemplified by the construction of settlements and transportation systems in patterns driven as much by cultural as by environmental constraints (Pickett and Cadenasso 1995).

All three of these drivers of heterogeneity undoubtedly interact in patterning the terrestrial biosphere, but their relative roles at global scales have yet to be studied and surely merit further investigation, considering the impacts of landscape fragmentation on biodiversity (Vitousek *et al*. 1997; Sanderson *et al*. 2002).

A conceptual model for anthropogenic biomes

Given that anthropogenic biomes are mosaics – mixtures of settlements, agriculture, forests and other land uses and land covers – how do we proceed to a general ecological understanding of human–ecosystem interactions within and across anthropogenic biomes? Before developing

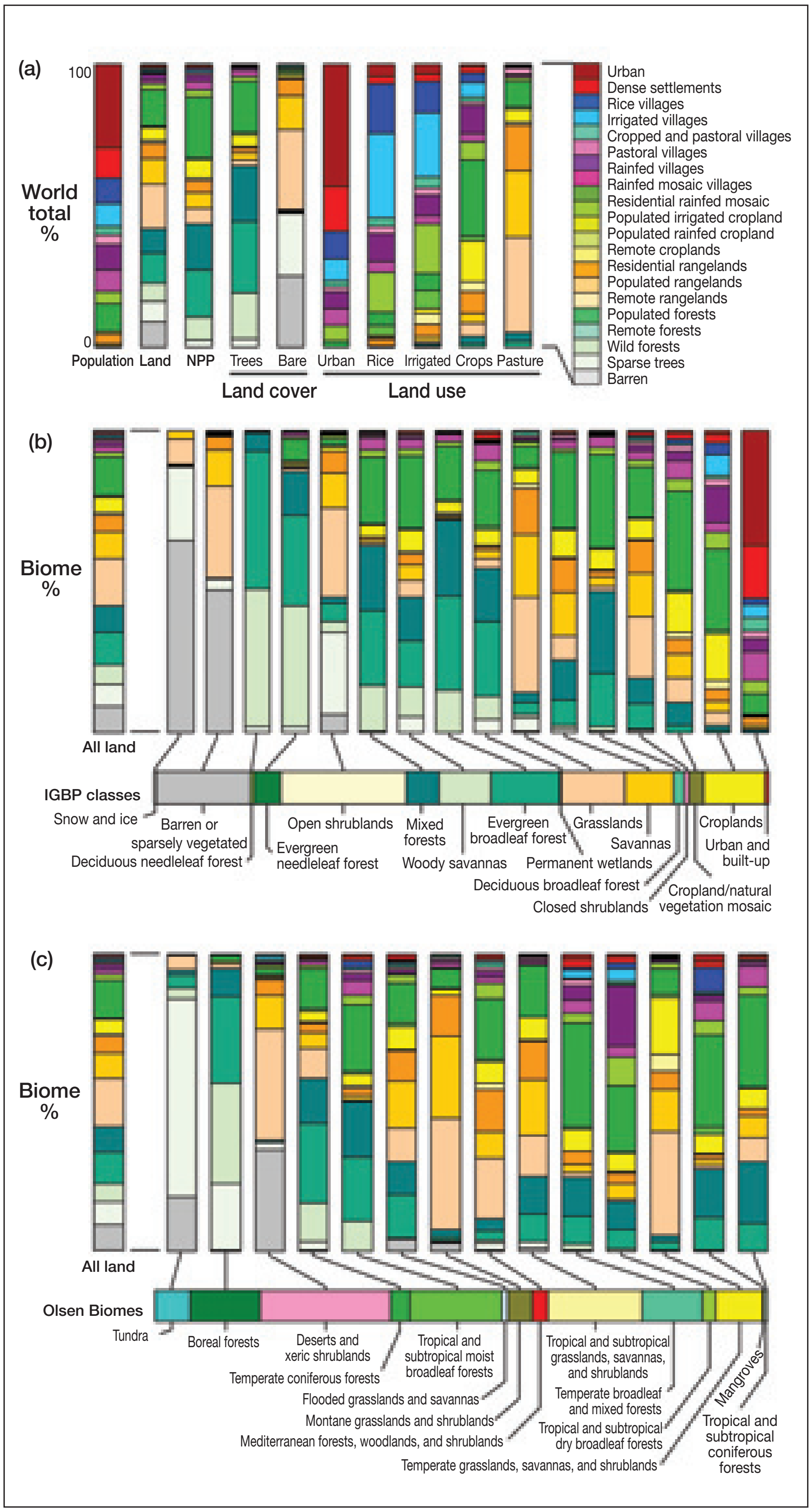

Figure 2*. Anthropogenic biomes expressed as a percentage of (a) global population, ice-free land, NPP, land cover, and land use use (WebTable 3), (b) IGBP land-cover classes (Friedl* et al. *2002; WebTable 4), and (c) Olson biomes (Olson* et al. *2001; WebTable 5). In (b) and (c), left columns show the anthropogenic biomes as a percentage of global ice-free land, horizontal bars show (b) IGBP land cover and (c) Olson biomes as a percentage of ice-free land, and columns in center illustrate the percent area of each anthropogenic biome within each IGBP and Olson class, sorted in order of decreasing total wild biome area, left to right. Color and order of anthropogenic biome classes is the same as in Figure 1.*

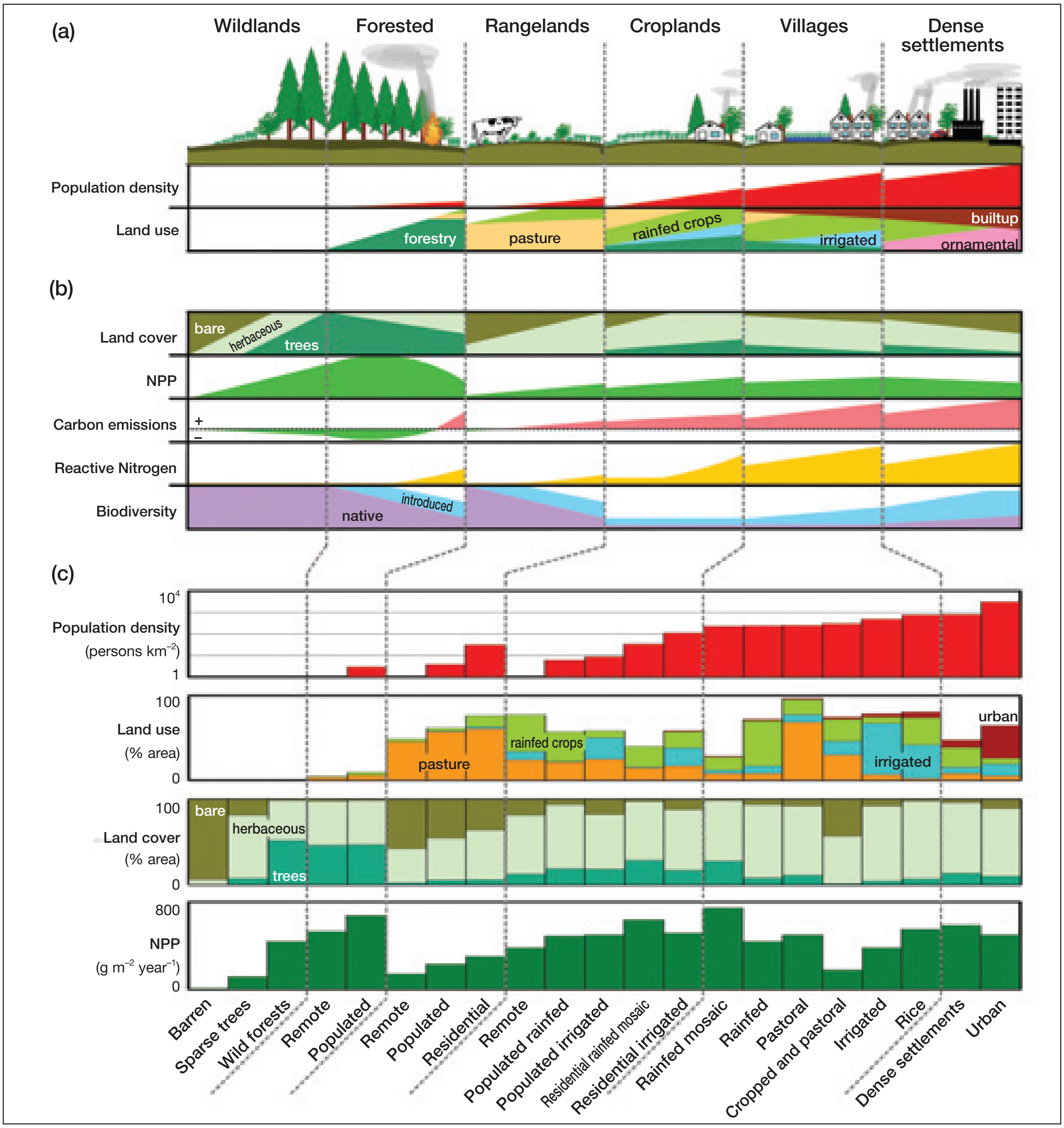

Figure 3. *Conceptual model of anthropogenic biomes compared with data. (a) Anthropogenic biomes structured by population density (logarithmic scale) and land use (percent land area), forming patterns of (b) ecosystem structure (percent land cover), process (NPP, carbon balance; red = emissions, reactive nitrogen) and biodiversity (native versus non-native + domestic biodiversity; indicated relative to pre-existing biodiversity; white space indicates net reduction of biodiversity) within broad groups of anthropogenic biomes. (c) Mean population density, land use, land cover, and NPP observed within anthropogenic biomes (Figure 1; WebTable 1). Biome labels at bottom omit names of broad groups, at top.*

a set of hypotheses and a strategy for testing them, we first summarize our current understanding of how these interactions pattern terrestrial ecosystem processes at a global scale using a simple equation:

Ecosystem processes = f(population density, land use, biota, climate, terrain, geology)

Those familiar with conventional ecosystem-process models will recognize that ours is merely an expansion of these, adding human population density and land use as parameters to explain global patterns of ecosystem processes and their changes. With some modification, conventional land-use and ecosystem-process models should therefore be capable of modeling ecological changes within and across anthropogenic biomes (Turner *et al.* 1995; DeFries *et al.* 2004; Foley *et al.* 2005). We include population density as a separate driver of ecosystem processes, based on the principle that increasing population densities can drive greater intensity of land use (Boserup 1965, 1981) and can also increase the direct contribution of humans to local ecosystem processes (eg resource consumption, combustion, excretion; Imhoff *et al.* 2004). For example, under the same environmental conditions, our model would predict greater fertilizer and water inputs to agricultural land in areas with higher population densities, together with greater emissions from the combustion of biomass and fossil fuel.

Some hypotheses and their tests

Based on our conceptual model of anthropogenic biomes, we propose some basic hypotheses concerning their utility as a model of the terrestrial biosphere. First, we hypothesize that anthropogenic biomes will differ substantially in terms of basic ecosystem processes (eg NPP, carbon emissions, reactive nitrogen; Figure 3b) and biodiversity (total, native) when measured across each biome in the field, and that these differences will be at least as great as those between the conventional biomes when observed using equivalent methods at the same spatial scale. Further, we hypothesize that these differences will be driven by differences in population density and land use between the biomes (Figure 3a), a trend already evident in the general tendency toward increasing cropped area, irrigation, and rice production with increasing population density (Figure 3c). Finally, we hypothesize that the degree to which anthropogenic biomes explain global patterns of ecosystem processes and biodiversity will increase over time, in tandem with anticipated future increases in human influence on ecosystems.

The testing of these and other hypotheses awaits improved data on human–ecosystem interactions obtained by observations made within and across the full range of anthropogenic landscapes. Observations within anthropogenic landscapes capable of resolving individually managed land-use features and built structures are critical, because this is the scale at which humans interact directly with ecosystems and is also the optimal scale for precise measurements of ecosystem parameters and their controls (Ellis *et al.* 2006). Given the considerable effort involved in making detailed measurements of ecological and human systems across heterogeneous anthropogenic landscapes, this will require development of statistically robust stratified-sampling designs that can support regional and global estimates based on relatively small landscape samples within and across anthropogenic biomes (eg Ellis 2004). This, in turn, will require improved global data, especially for human populations and land-use practices. Fortunately, development of these datasets would also pave the way toward a system of anthropogenic ecoregions capable of serving the ecological monitoring needs of regional and local stakeholders, a role currently occupied by conventional ecoregion mapping and classification systems (Olson *et al.* 2001).

Are conventional biome systems obsolete?

We have portrayed the terrestrial biosphere as composed of anthropogenic biomes, which might also be termed "anthromes" or "human biomes" to distinguish them from conventional biome systems. This begs the question: are conventional biome systems obsolete? The answer is certainly "no". Although we have proposed a basic model of ecological processes within and across anthropogenic biomes, our model remains conceptual, while existing models of the terrestrial biomes, based on climate, terrain, and geology, are fully operational and are useful for predicting the future state of the biosphere in response to climate change (Melillo *et al.* 1993; Cox *et al.* 2000; Cramer *et al.* 2001).

On the other hand, anthropogenic biomes are in many ways a more accurate description of broad ecological patterns within the current terrestrial biosphere than are conventional biome systems that describe vegetation patterns based on variations in climate and geology. It is rare to find extensive areas of any of the basic vegetation forms depicted in conventional biome models outside of the areas we have defined as wild biomes. This is because most of the world's "natural" ecosystems are embedded within lands altered by land use and human populations, as is apparent when viewing the distribution of IGBP and Olson biomes within the anthropogenic biomes (Figure 2 b,c).

Ecologists go home!

Anthropogenic biomes point to a necessary turnaround in ecological science and education, especially for North Americans. Beginning with the first mention of ecology in school, the biosphere has long been depicted as being composed of natural biomes, perpetuating an outdated view of the world as "natural ecosystems with humans disturbing them". Although this model has long been challenged by ecologists (Odum 1969), especially in Europe and Asia (Golley 1993), and by those in other disciplines (Cronon 1983), it remains the mainstream view. Anthropogenic biomes tell a completely different story, one of "human systems, with natural ecosystems embedded within them". This is no minor change in the story we tell our children and each other. Yet it is necessary for sustainable management of the biosphere in the 21st century.

Anthropogenic biomes clearly show the inextricable intermingling of human and natural systems almost everywhere on Earth's terrestrial surface, demonstrating that interactions between these systems can no longer be avoided in any substantial way. Moreover, human interactions with ecosystems mediated through the atmosphere (eg climate change) are even more pervasive and are disproportionately altering the areas least impacted by humans directly (polar and arid lands; IPCC 2007; Figure 1). Sustainable ecosystem management must therefore be directed toward developing and maintaining beneficial interactions between managed and natural systems, because avoiding these interactions is no longer a practical option (DeFries *et al.* 2004; Foley *et al.* 2005). Most importantly, though still at an early stage of development, anthropogenic biomes offer a framework for incorporating humans directly into global ecosystem models, a capability that is both urgently needed and as yet unavailable (Carpenter *et al.* 2006).

Ecologists have long been known as the scientists who travel to uninhabited lands to do their work. As a result, our understanding of anthropogenic ecosystems remains poor when compared with the rich literature on "natural" ecosystems. Though much recent effort has focused on integrating humans into ecological research (Pickett *et al.* 2001; Rindfuss *et al.* 2004; WebPanel 3 includes more citations) and support for this is increasingly available from the US National Science Foundation (www.nsf.gov; eg HERO, CNH, HSD programs), ecologists can and should do more to "come home" and work where most humans live. Building ecological science and education on a foundation of anthropogenic biomes will help scientists and society take ownership of a biosphere that we have already altered irreversibly, and moves us toward understanding how best to manage the anthropogenic biomes we live in.

Conclusions

Human influence on the terrestrial biosphere is now pervasive. While climate and geology have shaped ecosystems and evolution in the past, our work contributes to the growing body of evidence demonstrating that human forces may now outweigh these across most of Earth's land surface today. Indeed, wildlands now constitute only a small fraction of Earth's land. For the foreseeable future, the fate of terrestrial ecosystems and the species they support will be intertwined with human systems: most of "nature" is now embedded within anthropogenic mosaics of land use and land cover. While not intended to replace existing biome systems based on climate, terrain, and geology, we hope that wide availability of an anthropogenic biome system will encourage a richer view of human–ecosystem interactions across the terrestrial biosphere, and that this will, in turn, guide our investigation, understanding, and management of ecosystem processes and their changes at global and regional scales.

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WebTable 1. Mean population density, land use, land cover, and NPP within each anthropogenic biome

Biome		Population density Total (persons km^{-2})	Non-urban	Urban	Pasture	Crops	Cover Irrigated (%)	Rice	Trees	Bare	NPP (g m^{-2})
Dense settlements		*1788*	*440*	*21*	*6.9*	*26.3*	*10*	*6.3*	*12.3*	*6.7*	*550*
11	Urban	3172	543	38.3	5.6	20.5	14	7.8	10.3	10.9	500
12	Dense settlements	807	367	8.6	7.9	30.5	7.2	5.2	13.7	3.7	590
Villages		*327*	*210*	*2.3*	*15.6*	*45.7*	*17.3*	*11.4*	*13.3*	*7.8*	*520*
21	Rice villages	774	394	6.7	1.9	71.9	40.4	62.3	6.8	2.1	550
22	Irrigated villages	500	308	3.8	7	67.6	60.1	9.1	4.4	7.6	380
23	Cropped and pastoral villages	300	163	2.3	29.8	42.3	15.9	1	1.2	43	180
24	Pastoral villages	256	173	1.6	68.8	26.4	8.3	2.1	11.7	7.7	500
25	Rainfed villages	243	183	1.4	8.1	62.7	8.4	10.3	8.4	6.6	440
26	Rainfed mosaic villages	230	163	1.5	8.3	18.9	3.6	4.3	27.8	1.1	750
Croplands		*33*	*27*	*0.2*	*16.9*	*30.4*	*3.5*	*1.3*	*24.6*	*5.2*	*580*
31	Residential irrigated cropland	114	59	1.3	16.9	40.3	20.8	7.4	17.4	12.1	520
32	Residential rainfed mosaic	36	34	0.1	14.4	25.3	1	0.6	28.9	2.4	640
33	Populated irrigated cropland	9	5	0.1	24.5	34.2	25.7	4.8	18.1	17.5	500
34	Populated rainfed cropland	6	6	0	21.1	36	0.7	0.4	18.8	6.4	490
35	Remote croplands	1	0	0	24.1	53.5	9.7	1.2	12.8	18.2	380
Rangelands		*7*	*6*	*0*	*51.4*	*6*	*0.5*	*0.1*	*4.2*	*50.4*	*190*
41	Residential rangelands	32	30	0	60.6	16.1	1.8	0.2	6.2	36.1	300
42	Populated rangelands	4	4	0	57.4	4.8	0.4	0.1	5.8	45.7	230
43	Remote rangelands	0	0	0	45.3	3.5	0.1	0	2.8	57.3	140
Forested		*1*	*1*	*0*	*4.6*	*2*	*0.1*	*0.1*	*46.4*	*1.8*	*590*
51	Populated forests	3	3	0	6	3.2	0.2	0.1	46.7	1.2	680
52	Remote forests	0	0	0	3.6	1.1	0	0	46.2	2.2	530
Wildlands		*0*	*0*	*0*	*0*	*0*	*0*	*0*	*16.7*	*36.7*	*170*
61	Wild forests	0	0	0	0	0	0	0	51.7	1.3	440
62	Sparse trees	0	0	0	0	0	0	0	7.4	18.4	120
63	Barren	0	0	0	0	0	0	0	0.1	93.4	10
Global mean		45	23	0.4	18.6	10.3	1.8	0.9	20.4	25.8	360

WebTable 2. Global population, land use, land cover, and NPP in each anthropogenic biome

Biome		Population Total	Population Urban	Area Total	Area Urban	Area Pasture	Area Crops	Area Irrigated	Area Rice	Area Trees	Area Bare	NPP
		10^9 persons (%)		Area (10^6 km^2) (%)								Pg (%)
Dense settlements		*2.57 (40.3)*	*2.1 (64.1)*	*1.46 (1.1)*	*0.3 (56.7)*	*0.11 (0.4)*	*0.45 (3)*	*0.17 (6.3)*	*0.12 (7.2)*	*0.2 (0.7)*	*0.11 (0.3)*	*0.68 (1.4)*
11	Urban	1.87	1.68	0.6	0.22	0.04	0.15	0.1	0.07	0.07	0.08	0.2
12	Dense settlements	0.70	0.42	0.86	0.08	0.07	0.3	0.07	0.05	0.13	0.04	0.5
Villages		*2.56 (40.2)*	*0.99 (30.1)*	*7.71 (5.9)*	*0.18 (34.6)*	*1.21 (4.3)*	*3.64 (24.3)*	*1.38 (50.2)*	*1.14 (66.2)*	*1.05 (3.8)*	*0.62 (1.7)*	*3.87 (7.7)*
21	Rice villages	0.57	0.3	0.74	0.05	0.01	0.54	0.3	0.3	0.05	0.02	0.4
22	Irrigated villages	0.52	0.21	1.04	0.04	0.07	0.71	0.63	0.51	0.05	0.08	0.4
23	Cropped and pastoral villages	0.19	0.09	0.64	0.01	0.19	0.27	0.1	0.05	0.01	0.28	0.1
24	Pastoral villages	0.21	0.07	0.82	0.01	0.57	0.21	0.07	0.04	0.1	0.06	0.4
25	Rainfed villages	0.57	0.15	2.31	0.03	0.18	1.45	0.2	0.17	0.2	0.16	1.0
26	Rainfed mosaic villages	0.5	0.16	2.16	0.03	0.19	0.45	0.09	0.07	0.65	0.03	1.6
Croplands		*0.93 (14.5)*	*0.18 (5.4)*	*27.26 (20.8)*	*0.04 (8.1)*	*4.71 (16.8)*	*7.95 (53)*	*0.97 (35.3)*	*0.4 (23.4)*	*7.1 (25.3)*	*1.39 (3.9)*	*16.03 (32)*
31	Residential irrigated cropland	0.27	0.13	2.39	0.03	0.4	0.97	0.48	0.24	0.44	0.29	1.2
32	Residential rainfed mosaic	0.61	0.04	16.71	0.01	2.49	4.02	0.16	0.08	5.07	0.4	10.8
33	Populated irrigated cropland	0.01	0	0.73	0	0.17	0.25	0.18	0.06	0.14	0.13	0.4
34	Populated rainfed cropland	0.04	0	6.45	0	1.41	2.2	0.05	0.01	1.3	0.4	3.2
35	Remote croplands	0	0	0.99	0	0.24	0.51	0.1	0.01	0.14	0.17	0.4
Rangeland		*0.28 (4.3)*	*0.01 (0.4)*	*39.74 (30.4)*	*0 (0.7)*	*20.6 (73.4)*	*2.37 (15.8)*	*0.2 (7.3)*	*0.05 (3)*	*1.76 (6.3)*	*20.21 (56.8)*	*7.76 (15.5)*
41	Residential rangelands	0.23	0.01	7.31	0	4.46	1.15	0.12	0.04	0.48	2.61	2.2
42	Populated rangelands	0.04	0	11.52	0	6.6	0.54	0.05	0.01	0.71	5.25	2.8
43	Remote rangelands	0	0	20.91	0	9.54	0.68	0.03	0	0.58	12.35	2.8
Forested		*0.04 (0.6)*	*0 (0)*	*25.32 (19.3)*	*0 (0)*	*1.42 (5.1)*	*0.58 (3.9)*	*0.02 (0.9)*	*0 (0.3)*	*12.61 (44.9)*	*0.38 (1.1)*	*16.42 (32.8)*
51	Populated forests	0.04	0	11.23	0	0.78	0.39	0.02	0	5.52	0.12	8.1
52	Remote forests	0	0	14.09	0	0.64	0.19	0.01	0	7.1	0.26	8.3
Wildlands		*0 (0)*	*0*	*29.41 (22.5)*	*0 (0)*	*0 (0)*	*0 (0)*	*0 (0)*	*0 (0)*	*5.38 (19.1)*	*20.75 (58.3)*	*5.34 (10.7)*
61	Wild forests	0	0	8.2	0	0	0	0	0	4.58	0.09	4.1
62	Sparse trees	0	0	9.72	0	0	0	0	0	0.79	9.72	1.2
63	Barren	0	0	11.48	0	0	0	0	0	0.01	10.93	0.1
Global total		6.38	3.28	130.9	0.53	28.05	14.99	2.74	1.73	28.11	35.59	50.1

Notes: Biome groups include percentage statistics in parentheses

WebTable 3. Anthropogenic biome areas within different global regions (in km^2)

Biome		North America, Australia, and New Zealand	Europe (developed)	Asia and Oceania	Eurasia (developing)	Near East	Latin America and Caribbean	Africa	Global
11	Urban	151 096	52 332	232 251	47 196	42 853	49 791	21 279	596 798
12	Dense settlements	80 704	92 689	465 836	70 529	10 988	57 143	81 084	858 973
21	Rice villages	74		736 729	123	4 838		1 796	743 561
22	Irrigated villages	2561	29 867	905 975	58 119	28 366	12 192	2 581	1 039 661
23	Cropped and pastoral villages	7664	6961	276 941	53 635	174 376	12 681	104 914	637 172
24	Pastoral villages	7716	44 974	398 912	45 666	40 596	98 255	188 457	824 577
25	Rainfed villages	14 236	171 102	1 644 274	178 396	31 929	71 746	197 897	2 309 580
26	Rainfed mosaic villages	119 484	219 869	1 005 074	131 641	9 857	180 485	490 575	2 156 985
31	Residential irrigated cropland	282 271	122 828	1 178 061	260 781	192 429	212 790	143 592	2 392 752
32	Residential rainfed mosaic	1 505 043	1 375 762	3 171 805	2 879 954	105 278	2 817 358	4 850 072	16 705 271
33	Populated irrigated cropland	241 842	16 766	183 357	72 904	66 796	125 809	20 902	728 377
34	Populated rainfed cropland	1 212 832	205 910	545 859	1 583 644	44 693	1 441 961	1 411 470	6 446 369
35	Remote croplands	720 438	1935	136 030	24 515	22 745	74 896	6 373	986 932
41	Residential rangelands	137 798	117 445	1 196 738	504 336	1 270 533	901 817	3 182 426	7 311 093
42	Populated rangelands	516 385	31 185	1 727 998	1 580 710	1 421 436	2 336 449	3 907 966	11 522 131
43	Remote rangelands	6 895 517	77 913	2 127 531	3 654 199	2 467 347	2 259 096	3 427 138	20 908 741
51	Populated forests	1 248 457	509 554	1 713 507	1 889 752	9 648	3 012 663	2 845 953	11 229 535
52	Remote forests	2 759 665	327 685	893 227	4 377 191	1 697	4 689 130	1 046 188	14 094 783
61	Wild forests	3 384 243	100 134	11 119	2 638 756	na	1 931 837	138 662	8 204 751
62	Sparse trees	5 126 342	156 946	605	4 413 093	7 945	10 181	9 565	9 724 677
63	Barren	2 094 136	26 829	840 686	755 860	5 357 534	100 513	2 301 101	11 476 659
	Global	26 508 503	3 68 687	19 392 513	25 221 002	11 311 885	20 396 793	24 379 993	130 899 376

WebTable 4. Anthropogenic biome areas within each IGBP land cover class (in km^2)

Biome	IGBP class	Evergreen needleleaf forest Class 1	Evergreen broadleaf forest Class 2	Deciduous needleleaf forest Class 3	Deciduous broadleaf forest Class 4	Mixed forests Class 5	Closed shrubland Class 6	Open shrubland Class 7	Woody savannas Class 8	Savannas Class 9	Grassland Class 10	Permanent wetlands Class 11	Croplands Class 12	Urban and built-up Class 13	Cropland natural vegetation mosaic Class 14	Snow and ice Class 15	Barren or sparsely vegetated Class 16	Global
11	Urban	12204	21089	56	7294	19347	4143	21755	20770	17648	16214	3213	151239	276922	21121	na	11027	604041
12	Dense settlements	17991	56550	93	14834	45379	7904	22711	65725	52982	27390	5157	355090	127523	62174	1	6601	868105
21	Rice villages	4420	24772	32	4219	21441	4579	7259	27690	18177	6317	2054	554110	13000	40568	na	3691	732331
22	Irrigated villages	2126	4277	12	1636	8944	4235	32014	10424	13431	11638	647	875122	34571	26241	na	5531	1030850
23	Cropped and pastoral villages	307	290	na	144	247	6763	178072	3350	14566	156414	67	154949	31297	1908	na	83974	632349
24	Pastoral villages	3182	16669	30	7987	34658	9995	59354	72143	121633	114544	743	302129	15768	54675	2	6924	820437
25	Rainfed villages	7605	35740	49	14483	44429	17112	115902	116752	105953	77212	2001	1606866	33960	99668	na	11329	2289061
26	Rainfed mosaic villages	69013	342529	358	84000	261981	20586	35335	353019	255422	88521	16784	382376	69503	184745	8	9780	2173960
31	Residential irrigated cropland	33926	237336	179	52612	152370	20105	261576	237784	148596	206017	9328	757239	31730	127579	9	88665	2365053
32	Residential rainfed mosaic	418327	2571084	4221	712770	1514097	132885	545285	2614069	2567188	929185	56891	3472303	50684	996757	133	59278	16645158
33	Populated irrigated cropland	8470	122570	47	12587	22062	4323	88109	54398	40658	108438	4122	165934	1116	33698	3	53482	720019
34	Populated rainfed cropland	82922	533374	1463	159778	270587	54510	382564	814177	917056	644953	16058	2069684	3186	400656	53	40794	6391816
35	Remote croplands	5804	122614	280	7595	14485	2830	78610	52885	26168	221837	1073	351664	102	64114	8	28776	978844
41	Residential rangelands	9641	65361	89	49719	49836	85512	1855652	417735	1156250	2026988	3059	532681	20533	156614	461	845507	7275637
42	Populated rangelands	26018	105531	582	70053	66646	115914	3088191	572335	1458077	2822344	8973	471365	7745	243063	9663	2396277	11462778
43	Remote rangelands	68031	63831	1682	37077	61460	161508	7751587	602013	812480	4267219	9638	554429	4593	250750	33083	6058157	20737540
51	Populated forests	808913	3694646	54599	635359	1479453	65807	480859	1590201	1362468	386238	54101	219674	3933	234331	366	31162	11102109
52	Remote forests	1700923	4549322	422097	412093	1695214	65471	1641143	1652262	860471	586854	76004	106483	807	69988	1816	25353	13866300
61	Wild forests	2276116	2063737	421192	37411	1017770	4222	858369	1083566	102027	159459	23521	2129	65	1373	529	2070	8053556
62	Sparse trees	101527	3870	18771	5290	36204	5775	7155117	562167	120177	574417	13492	1475	76	493	94938	667148	9360938
63	Barren	1647	49	11	29	839	973	1613079	11832	4243	53973	24	11	121	0	247526	9398770	11333229
	Global	5659113	14635342	925843	2326974	6817450	795152	26272544	10935296	10175672	13486172	306953	13086952	727236	3070518	388599	19834297	129444112

WebTable 5. Anthropogenic biome areas within each Olson biome (in km^2; Olson *et al.* 2001)

Biome	Olsen class	Tropical and sub-tropical moist broadleaf forests 1	Tropical and sub-tropical broadleaf forests 2	Tropical and sub-tropical coniferous forests 3	Temperate broadleaf and forests 4	Temperate coniferous forests 5	Boreal forests 6	Tropical and sub-tropical grasslands savannas and shrublands 7	Temperate grasslands savannas and shrublands 8	Flooded grasslands and savannas 9	Montane grasslands and shrublands 10	Tundra 11	Mediterranean forests, woodlands, and shrub 12	Deserts and xeric shrublands 13	Mangrove 14	Global
11	Urban	141 319	27 370	3 248	204 826	20 942	5 083	20 588	50 908	21 665	4 568	177	37 019	52 410	6 460	596 584
12	Dense settlements	253 141	59 483	9 135	352 118	1 171	6 029	43 263	31 682	3 340	12 934	379	31 751	27 887	6 455	858 767
21	Rice villages	492 834	57 067		105 476	586		14 454	58	4 341			210	46 794	21 553	743 373
22	Irrigated villages	180 339	120 115	1 454	384 663	7 170		4 905	33 202	9 494	61		23 501	272 281	2 475	1 039 661
23	Cropped and pastoral villages	9 920	37 914	390	55 379	6 435	64	91 294	55 415	11 115	39 538	107	52 163	277 216	153	637 103
24	Pastoral villages	244 260	14 223	5 115	224 469	5 824	474	140 631	45 123	7 050	46 922		39 219	40 440	827	824 577
25	Rainfed villages	458 364	610 367	10 169	665 170	12 000	1 637	135 129	60 064	14 602	36 403		67 356	232 767	5 552	2 309 580
26	Rainfed mosaic villages	943 448	111 742	49 487	551 689	63 361	19 508	209 405	10 885	5 616	97 264	688	55 550	19 102	18 437	2 156 184
31	Residential irrigated cropland	667 531	297 012	19 429	419 816	45 439	7 763	119 890	206 626	31 367	24 176	568	171 069	368 043	13 705	2 392 435
32	Residential rainfed mosaic	4 393 091	656 671	216 700	4 471 565	551 174	298 892	3 464 835	837 452	146 251	349 210	13 372	651 244	567 741	85 315	16 703 512
33	Populated irrigated cropland	159 362	28 726	4 673	86 695	29 938	2 989	72 109	145 662	10 875	8 125	83	28 763	143 058	7 208	728 268
34	Populated rainfed cropland	839 308	180 366	47 116	911 092	144 168	151 233	1 534 794	1 935 141	88 832	108 737	10 632	230 946	244 424	18 322	6 445 112
35	Remote croplands	127 703	15 778	1 818	40 925	28 225	4 203	47 434	544 922	3 376	2 827	870	66 600	101 576	613	986 870
41	Residential rangelands	527 855	103 841	17 640	540 439	123 550	5 183	2 653 689	627 603	110 648	736 239	626	446 575	1 412 189	4 947	7 311 023
42	Populated rangelands	336 368	160 797	49 383	349 304	221 043	9 716	3 831 094	1 409 507	173 882	1 450 572	10 835	294 398	3 219 297	5 448	11 521 643
43	Remote rangelands	50 800	28 877	59 042	219 264	408 641	223 044	2 771 046	3 551 075	127 012	1 994 683	352 763	649 536	10 468 255	2 935	20 906 971
51	Populated forests	3 727 390	278 858	146 221	1 688 904	600 323	1 370 058	2 538 963	176 619	119 344	113 330	126 311	122 121	173 936	44 818	11 227 196
52	Remote forests	4 264 839	195 985	65 414	1 191 644	1 091 496	4 362 437	1 880 048	281 943	158 425	82 533	344 885	112 418	30 219	31 190	14 093 476
61	Wild forests	1 992 640	20 910	735	242 630	535 305	4 995 563	67 699	47 841	3 096	18 034	265 087	13 665	821	700	8 204 726
62	Sparse trees	639	36		2 680	104 439	3 348 988	394 752	4 925	2 129	20 807	5 039 899	86 978	689 910	206	9 696 388
63	Barren		2		41 187	19 942	64 891	231 764	5 071	44 921	146 949	1 365 215	10 259	9 502 039		11 432 240
	Global	19 811 155	3 006 139	707 169	12 749 934	4 051 173	14 877 757	20 267 785	10 061 725	1 097 382	5 293 912	7 532 496	3 191 341	27 890 403	277 319	130 815 689

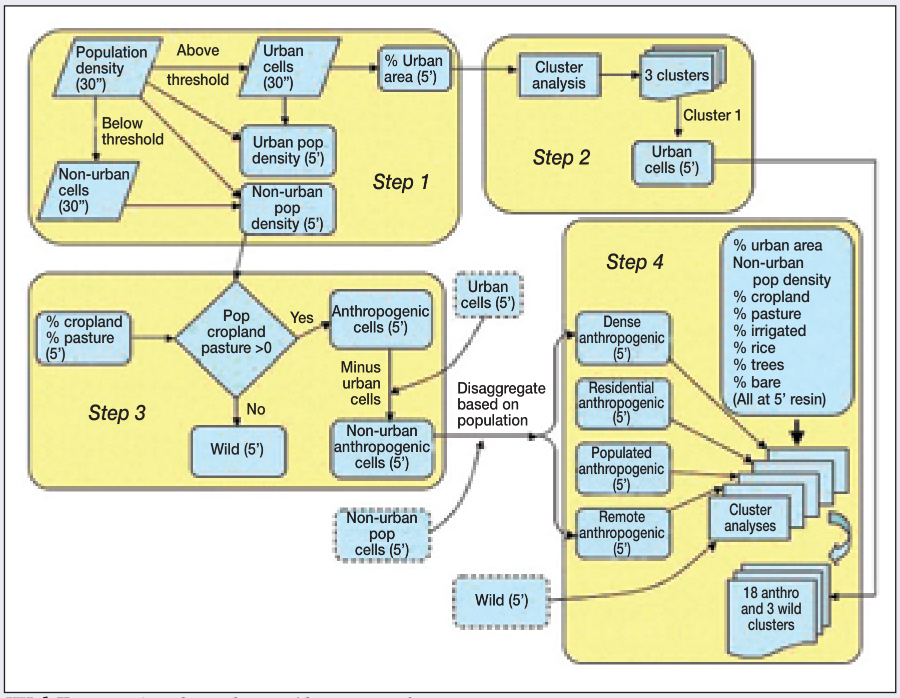
WebPanel 1. Methods used in global analysis

We identified and mapped anthropogenic biomes using a multi-stage empirical process (illustrated below in WebFigure 1) based on global data for:

- **population** (Landscan 2005; 30 arc second resolution: 30" cells cover ~ 0.86 km^2 at the equator; all geographic resolutions decrease in size toward the poles; Dobson *et al*. 2000; Oak Ridge National Laboratory 2006)
- **land use** (percent area of **pastures, crops, irrigated**, and **rice**; 5 arc minute resolution: 5' grid cells cover ~ 86 km^2 at the equator; irrigation data from Siebert *et al.* [2005], Ramankutty *et al.* [in press], and Monfreda *et al.* [in press]; rice production requires flooding, making it perhaps the most intensive type of agriculture; rice percent area was calculated as percent irrigated cover for cells with rice)
- **land cover** (percent area of **trees** and **bare earth**; 15 arc second data; 15" ~ 0.25 km^2 at the equator; Hansen *et al*. 2003).

Data for **percent urban area**, urban population, and non-urban population density were prepared from Landscan (2005) data, by classifying 30" cells with population density $\geq$ 2500 persons km^{-2} as urban and others as non-urban (except for North America, Australia, and New Zealand, where cells $\geq$ 1000 persons km^{-2} were classified as urban; these regions have no history of dense agricultural populations and tend to have lower urban densities as well). Data for net primary productivity (Zhao *et al*. 2005), IGBP land cover (Friedl *et al*. 2002, 2004), and Olson biomes (Olson *et al*. 2001) were also obtained for later analysis. We conducted our global analysis at 5 arc minute resolution because this offered the best compromise between data resolution and quality, based on our review of available global data. Prior to analysis, all data were aggregated into 5' cells, covering Earth's ice-free land (percentages and densities were averaged, populations were summed). Global and regional area estimates represent 5' cell areas (Mollweide-projected) adjusted for percent land within each cell at 30" resolution.

We first separated "anthropogenic" 5' cells from "wild" cells, based on the presence of human populations, crops, or pastures. Next, we used "two-step" cluster analysis (in SPSS 15.01) to separate the anthropogenic cells into our various biomes. Cluster analysis is a statistical procedure designed to identify an optimal number of distinct natural groupings (clusters) within a dataset (data were standardized prior to clustering using log-likelihood cluster distances and the Bayesian Information Criterion). We first extracted "urban" cells based on a cluster analysis of the **percent urban area** data, as the cluster of cells with the highest percent urban area (> 17.5%) among three clusters obtained for this variable. Anthropogenic cells were then stratified into the population density classes described in the main text ("dense", "residential", "populated", and "remote") based on their non-urban population densities. Two-step cluster analysis was then used again, to identify natural groupings within the cells of each population density class and within the wild class, based on non-urban population density, percent urban area, pasture, crops, irrigated, rice, trees, and bare earth. Finally, the strata derived above were described, labeled, and organized into broad logical groupings, based on their populations, land-use and land-cover characteristics and their regional distribution, yielding the 18 anthropogenic biome classes and three wild biome classes illustrated in Figure 1 and described in Table 1 (WebTables 3 and 5 include more detailed statistics; WebPanel 2 provides inks to the biome data in GIS format together with interactive maps in Google Earth and other formats, and a printable wall map).



WebFigure 1. Flow chart of biome analysis.

WebPanel 1 *continued*

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WebPanel 2. Spatial data

A) Interactive maps and printable wall map of anthropogenic biomes

Available from Encyclopedia of Earth

Interactive Maps viewable in:

www.eoearth.org/article/Anthropogenic_biome_maps

- Google Earth
- Google Maps
- Microsoft Virtual Earth

Wall map (30" x 50") in Adobe Acrobat format.

http://www.eoearth.org/eoe-maps/pdf/anthro_biomes_wall_map_v1.pdf

For printing on large format printers (>30 inch):

NOTE: Large download (~80MB)

To print the wall map:

1) Rotate page to vertical using the rotate button in the Acrobat menu bar.
2) Turn off "autorotate and center" and other scaling options
3) Set print size to 51" x 31" paper size.

B) GIS data available from Ecotope.org

Anthropogenic biomes map data in ArcInfo GRID format:

http://ecotope.org/files/anthromes/anthromes_v1.zip

This ZIP file contains an ArcInfo GRID file and an ArcGIS symbology layer (.lyr) for visualization using GIS software. Before using these data for publication, please contact Erle Ellis (ece@umbc.edu) for the most up-to-date version.

WebPanel 3. Recent literature on human–environment interactions

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