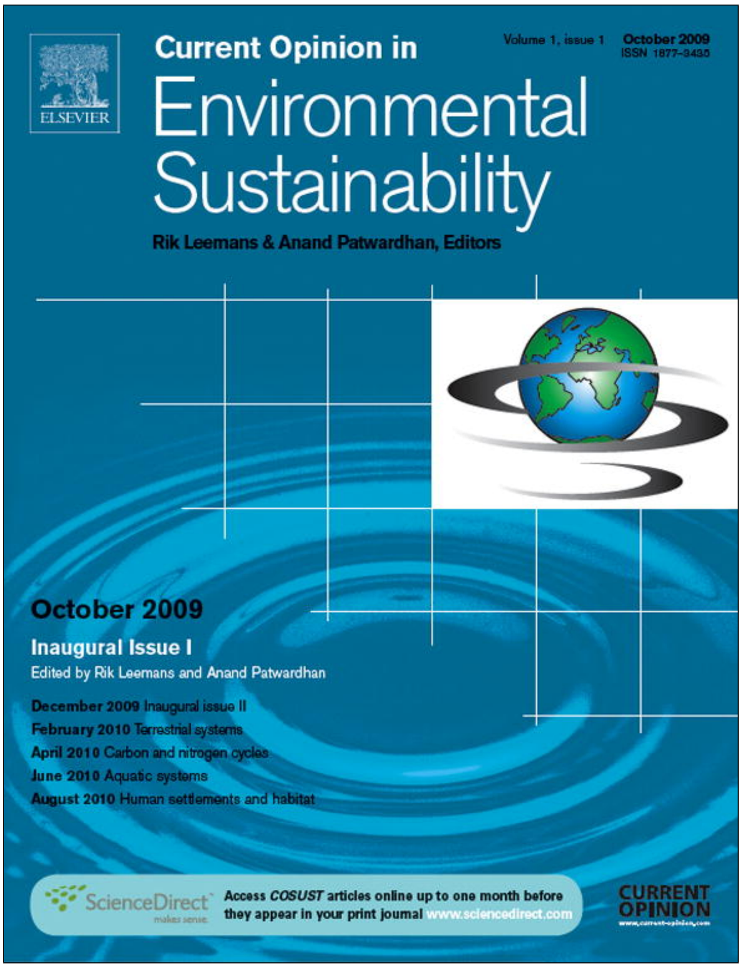
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Global urban land-use trends and climate impacts

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In 2008, the global urban population exceeded the nonrural population for the first time in history, and it is estimated that by 2050, 70% of the world population will live in urban areas, with more than half of them concentrated in Asia. Although there are projections of future urban population growth, there is significantly less information about how these changes in demographics correspond with changes in urban extent. Urban land-use and land-cover changes have considerable impacts on climate. It has been well established that the urban heat island effect is more significant during the night than day and that it is affected by the shape, size, and geometry of buildings as well as the differences in urban and rural gradients. Recent research points to mounting evidence that urbanization also affects cycling of water, carbon, aerosols, and nitrogen in the climate system. This review highlights advances in the understanding of urban land-use trends and associated climate impacts, concentrating on peer-reviewed papers that have been published over the last two years.

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Global urban land-use trends

Urbanization and climate change are two defining environmental phenomena of the 21st century, and these two processes are increasingly interconnected. This paper reviews recent developments in our understanding of global patterns of urban land-use and the effects of urbanization on climate. Currently, more than half of the world's population lives in urban areas, and it is expected that 70% will live in urban areas by 2050 [1]. Most of the urban demographic transformation in the coming decades will occur in Asia and Africa, and by 2050, one-third of all urban dwellers will be concentrated in Asia [2]. Nearly one-quarter of the world's population lives within 100 km of the coast [3] and 13% of the world's urban population lives less than 10 m above sea level [4••]. Missing from these forecasts of urban population growth are parallel and spatially explicit estimates of the rates, magnitudes, and shapes of urban land-use. Yet, time series information on land-use and land-cover has been specifically identified as data needed in order to understand the interactions between climate, humans, and environmental systems [5].

Remote sensing data have been widely used to measure urban extents, with a majority of studies using one to three satellite images to provide single snapshots of urban land-use or to monitor urban land-use change between two or three time points [6,7]. The Landsat satellite record now spans more than three decades and opens up new opportunities for the use of multiple satellite observations to generate high temporal frequency information about urban land-use [9,10]. New analytical techniques also are developed to extract urban characteristics from satellite data such as informal settlements [8,9], surface energy balance [10,11], and buildings and other urban geometric features [12,13].

How urban areas develop — whether expansive or compact, with multifamily residential complexes or single family homes, automobile dependent or enabling multiple forms of transportation, with mixed-use or single-use zoning — affects transportation choices and travel behavior [14,15], and determines infrastructure needs [16] and energy consumption [17]. Once in place, urban infrastructure is difficult to reverse, and their longevity leads to a path dependency with regard to energy use and may limit adaptation strategies to climate change and associated effects such as heat waves. *Where* urban areas develop — whether on the coast, in agricultural areas, in forested regions, or near existing urban centers — determine their vulnerability to climate change impacts such as sea level rise and storm surges, the need to expand agricultural production into other areas, and the resources required to provide urban services such as water, energy, and transportation infrastructure. In short, environmental impacts of urban form are indisputable.

Most of our understanding about global urban land-use comes from case studies on individual cities or regions [18–20]. Although coarse scale monitoring provides global and national estimates of urban areas, accuracy assessments of global urban maps indicate that there is a high degree of variance among estimates, suggesting caution in their use [21,22•]. From these individual case studies is emerging a picture of varied rates of urban land-use change around the world. Rates of urban land-use change are highest in Asia and some areas in South America and are strongly correlated with patterns of economic development [20,23]. When economic development is driven by shifts in the economy from agriculture to manufacturing, it leads to more expansive urban land-use change than the economic transition from manufacturing to services [24]. In many developing countries and export-oriented regions where economic growth is high, urban land-use change is growing faster than the rate of urban population growth. One study of 120 cities around the world shows that urban populations have been growing at 1.7% annually over the last two decades, but urban land-use change is growing faster, at more than 3.3% annually [23]. Worldwide, urban land-use change is driving landscape fragmentation [25–27], the loss of agricultural land [28,29], and threatening biodiversity [30••,31]. It is estimated that an area with the size of California will be converted to urban areas by 2030 [23].

Land change science, including urban land-use change, is emerging as a fundamental component of global environmental change [32]. Given the increasing importance of urban areas in driving and being impacted by global environmental change, there is urgent need to understand how urban areas evolve, and how and where they may develop in the future. There is a rapidly growing literature on modeling urban spatial dynamics and forecasting urban growth [36–39]. The general consensus is that urban land-use dynamics can be best understood as complex systems [33] with emergent properties such as obeying power laws [34,35]. In order to evaluate the efficacy of urban planning to direct urban development or conservation policies to save protected areas or limit urban expansion, it will be critical to develop conceptual frameworks and modeling approaches that can characterize the underlying processes that drive urban land-use dynamics [36], including the effect of roads and transportation corridors on urbanization patterns [37,38]. Furthermore, these methods will need to be applicable to the developing world where most of the urban growth will occur in the coming decades and where there are often limited data availability and accuracy [39].

Currently, our understanding of both current and future patterns of global urban land-use is poor and fragmented. This is largely due to an uneven global distribution of urban land-use studies. A majority of studies focus on urbanizing regions in China, India, Europe, and the United States, but there are comparatively few studies of urban land-use change in South America, Africa, and the rest of the world. The lack of understanding about past urban land-use processes limits our ability to identify regions at risk for urban development. However, these knowledge gaps also open myriad opportunities to take advantage of existing satellite data sets to expand our understanding of global urban land-use trends.

Climate impacts of urbanization

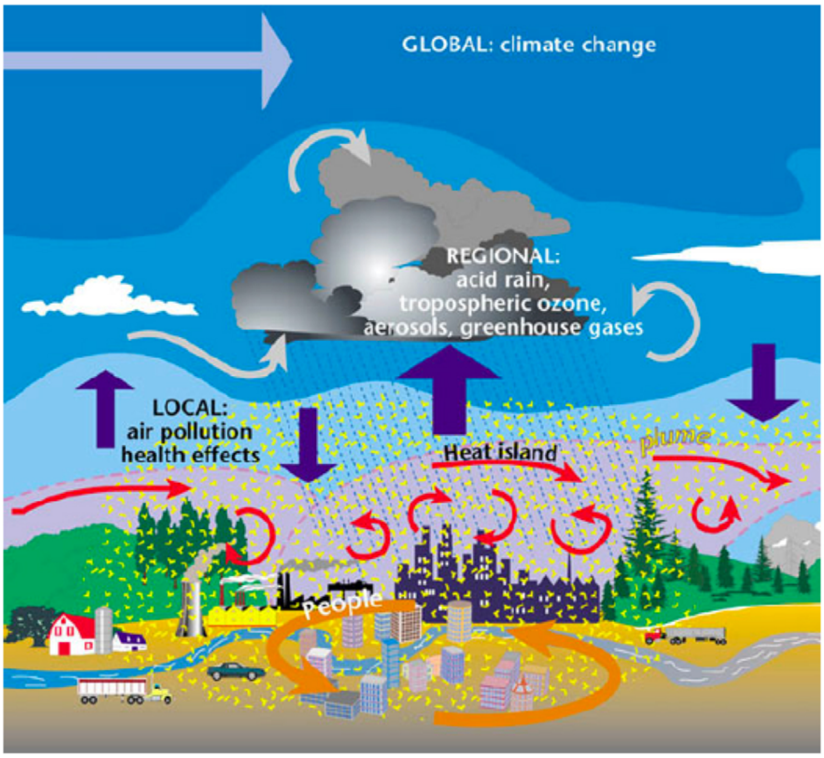
Concomitant with the rising interest in characterizing and forecasting urban land-use change is an increased understanding of the relationship between urbanization and climate. Though the effects of anthropogenic greenhouse gases have been the focus of prevailing climate change inquiry, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) noted the emerging interest in understanding the role of urban land-use on the climate system [40]. The built environment characterized by urbanization is a significant forcing function on the weather-climate system because it is a heat source, a poor storage system for water, an impediment to atmospheric motion, and a source of aerosols (e.g. pollutants) (Figure 1) [41•].

Such attributes significantly alter surface energy budgets, the hydrological cycle, and biogeochemical cycles related to carbon and nitrogen. Further, it is increasingly clear that the impact of urban land-use extends from local to global scales [42] (Table 1).

The most well-studied and familiar manifestation of urban climate modification is the urban heat island (UHI) [43,44]. Recent research shows that it is spatially correlated with regional land-use and land-use change. A landscape during the early phases of urban development is a patchwork of multiple land-covers, with bare land, vegetated areas, agricultural plots, and built-up areas in close proximity with one another. In non-desert environments, urbanization increases the contiguous urban extent and reduces the vegetated surfaces, and the spatial pattern of the urban heat island correspondingly becomes less scattered and more intense [45–47]. In desert cities, the urbanization process often increases vegetation. The role of the urban heat island on regional and global climate has been the subject of numerous investigations [48–53]. However, the role of urban land-use on climate extends well beyond the UHI.

Human activities associated with urban land-use (e.g. transportation, energy, and industrial processes) produce a clearly discernible association with 'urban' aerosols or pollution, and have been associated with elevated greenhouse gas emissions. Carbon dioxide concentrations in urban centers are significantly higher than in nonurban, rural areas [54], but per capita greenhouse gas emissions for urban dwellers may be lower than for country averages [55]. Efforts to inventory greenhouse gas emissions in urban areas are made more difficult by a lack of data to attribute both direct and indirect emissions to urbanization [56]. Back of the envelop calculations suggest that if greenhouse gas emissions were attributed to the producer rather than the consumer, cities emit between 30 and 40% of all greenhouse gas emissions, a figure that is significantly lower than the widely cited statistic that cities generate 75–80% of all greenhouse gas emissions [57].

Figure 1



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Physical interactions in the urban microclimate (from Hidalgo *et al.* [41]).

Aerosols affect climate, directly and indirectly, through radiative forcing. There are various types of aerosols over urban regions but the primary types are sulfates, nitrates, ammonium, organics, crustal rock particulate matter, sea salt hydrogen ions, and water [58]. Aerosols affect not only the local urban microclimate, ecosystem, and society but also the global climate. The 'direct' radiative effect of aerosols is to scatter, reflect, or absorb solar radiation. Most aerosols, including sulfates found in urban environments, promote a cooling effect in the radiative budget;

Table 1

Various pathways for urbanization to impact the climate system (see text for references)

	Urban land-cover	Urban aerosols	Anthropogenic greenhouse gas (GHG) emissions
Urban heat island and mean surface temperature record	Surface energy budget	Insolation, direct aerosol effect	Radiative warming and feedbacks
Wind flow and turbulence	Surface energy budget, urban morphological parameters, mechanical turbulence, bifurcated flow	Direct and indirect aerosol effects and related dynamic/ thermodynamic response	Radiative warming and feedbacks
Clouds and precipitation	Surface energy budget, UHI-destabilization, UHI meso-circulations, UHI-induced convergence zones	Aerosol indirect effects on cloud-precipitation microphysics, insolation effects	Radiative warming and feedbacks
Land surface hydrology	Surface runoff, reduced infiltration, less evapotranspiration	Aerosol indirect effects on cloud-microphysical and precipitation processes	Radiative warming and feedbacks
Carbon cycle	Replacement of high net primary productivity (NPP) land with impervious surface	Black carbon aerosols	Radiative warming and feedbacks, fluxes of carbon dioxide
Nitrogen cycle	Combustion, fertilization, sewage release, and runoff	Acid rain, nitrates	Radiative warming and feedback, NOx emissions

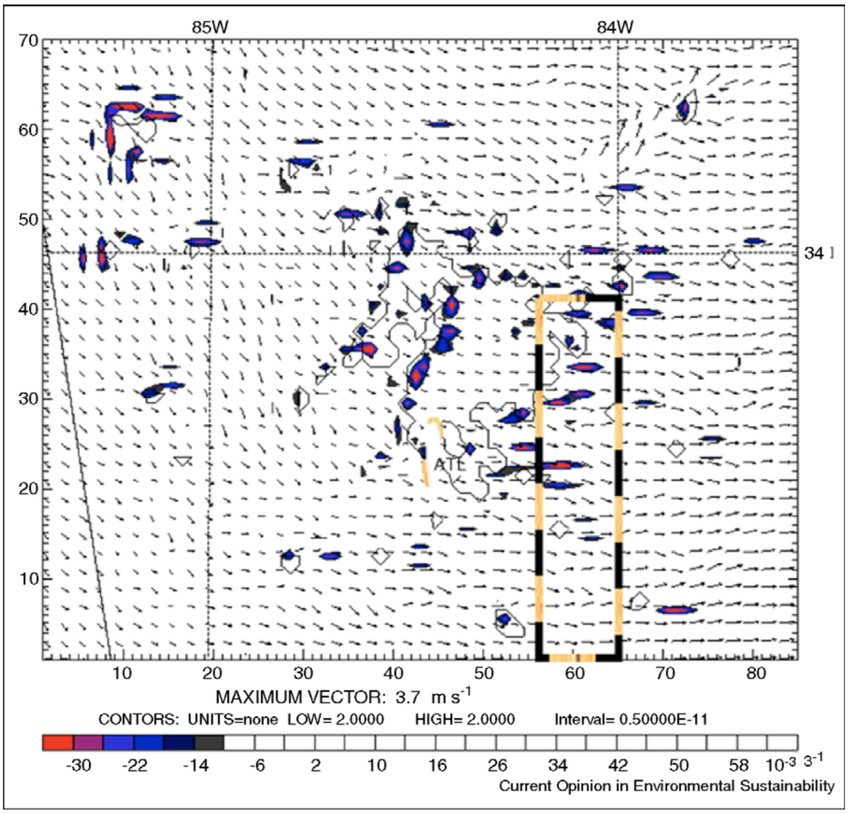
however, carbon-based aerosols absorb solar radiation and may warm the atmosphere and surface. Such warming can affect the atmospheric stability profile and thereby alter cloud and precipitation morphology.

Climate–aerosol interactions are quite complex and beyond the scope of this discussion, but it is clear from the emerging literature that the negative and positive effects must be placed in the context of scale: local, regional, and global. Emerging challenges will also include proper budgeting of aerosol types and concentrations at such scales and detangling the resulting feedbacks and responses across scales. For example, aerosols augment UHI-effects on temperature by absorbing, re-emitting, and scattering solar and terrestrial radiation. Anthropogenic aerosols also act as condensation nuclei or 'seeds' for cloud-microphysical processes [59]. This so-called 'indirect effect' of aerosols further perturbs the radiation budget, cloud distribution, and precipitation variability. Urban land-use also alters local and regional atmosphere dynamic and stability conditions to support thermally directed circulations similar to sea breezes. Historical and current literature has persistently shown that UHI-destabilization, urban surface roughness, and pollution can independently or synergistically initiate, modify, or enhance precipitation cloud systems [60,61].

There is renewed debate on the effects of urbanization on precipitation variability [62]. A growing body of literature suggests that urban land-use can create an increase in regional precipitation variability and intensity [60,63,64], known as the 'urban rainfall effect' [65•] (Figure 2). In Europe [66] and South China [67], there have been a few cases with observed decreases in winter rainfall compared to preurbanization periods. Further, urban land-use accelerates hydrologic response through surface runoff variability. While physical mechanisms continue to be investigated, it is important to properly characterize the role of urbanization on water cycle processes, as they are critical in diagnosing and predicting climate changes.

Two additional cycles important to climate are also sensitive to urban land-use changes. Net primary productivity (NPP), a measure of carbon, has recently been studied and quantified in relation to carbon balance and food production [68]. Urbanization takes place on Earth's most fertile lands and has a disproportionately large net negative effect on regional to continental scale

Figure 2



Model simulations from Shem and Shepherd [65•] illustrating how Atlanta, Georgia's urban land-cover induces low-level convergence (red and blue colors) and where urban-enhanced rainfall eventually occurred (rectangle).

NPP. Research suggests that NPP losses from urbanization alone are roughly equivalent to the caloric requirement of about 6% of the United States population annually [68]. Human activities in urban areas also significantly perturb land-atmosphere fluxes of carbon dioxide [69]. Global carbon budget analyses are central tenets of climate change science, and it is evident that they must properly account for the impacts of urban environments.

Urban land-use is also strongly correlated with high levels of combustion, fertilization, and sewage release. These processes release various forms of nitrogen compounds into the climate system and ecosystems [70]. Human-generated nitrous oxide releases contribute to global warming, ozone layer depletion, photochemical smog formation, and acid rain, while excess nitrogen destroys ecosystems through acidification of water bodies, tree deaths, and biodiversity reductions. Changes in major biogeochemical cycles, like the nitrogen cycle, are inter-related to climate processes.

Clearly, the footprint of urban land-use is apparent in Earth's climate system and must be accounted for in emerging climate modeling systems [71]. Huge uncertainties remain about the rate and magnitude of urban expansion: which ecosystems are most at risk to urban development, what are the emerging patterns of urban land-use, and how will extensive and expansive urban land-use change drive affect regional and global climate? As area estimates and mapping of global urban land-use improve and converge with ever-increasing spatial resolution of climate models (i.e. as grid cells cover smaller surface areas), the aforementioned urban forcing on atmospheric thermodynamics, dynamics, energy balance, microphysics, and composition must be explicitly represented. Only then will the climate science community make the necessary progress to understand the integrated effects of urban land-use, urban land-use change, and associated aerosol processes on climate.

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