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Assessing the global warming potential of human settlement expansion in a mesic temperate landscape from 2005 to 2050

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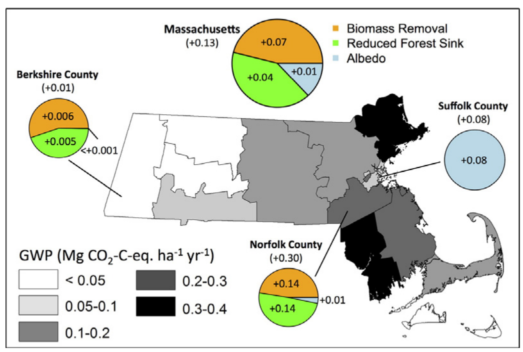
HIGHLIGHTS

- Human settlement expansion is an important driver of global change.
- We model biophysical implications of projected human settlement expansion.
- Reduced albedo and forest carbon sink result in positive global warming potential.
- Urban biomass carbon uptake can mitigate reductions in forest carbon sink.
- Essential to consider urban biomass and spatial patterns in biophysical response.

GRAPHICAL ABSTRACT



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ABSTRACT

Expansion of human settlements is an important driver of global environmental change that causes land use and land cover change (LULCC) and alters the biophysical nature of the landscape and climate. We use the state of Massachusetts, United States (U.S.) to present a novel approach to quantifying the effects of projected expansion of human settlements on the biophysical nature of the landscape. We integrate nationally available datasets with the U.S. Environmental Protection Agency's Integrated Climate and Land Use Scenarios model to model albedo and C storage and uptake by forests and vegetation within human settlements. Our results indicate a 4.4 to 14% decline in forest cover and a 35 to 40% increase in developed land between 2005 and 2050, with large spatial variability. LULCC is projected to reduce rates of forest C sequestration, but our results suggest that vegetation within human settlements has the potential to offset a substantial proportion of the decline in the forest C sink and may comprise up to 35% of the terrestrial C sink by 2050. Changes in albedo and terrestrial C fluxes are expected to result in a global warming potential (GWP) of +0.13 Mg CO_2–C-equivalence ha^{-1} year^{-1} under the baseline trajectory, which is equivalent to 17% of the projected increase in fossil fuel emissions. Changes in terrestrial C fluxes are generally the most important driver of the increase in GWP, but albedo change becomes an increasingly important component where housing densities are higher. Expansion of human settlements is the new face of LULCC and our results indicate that when quantifying the biophysical response it is essential to consider C uptake by vegetation within human settlements and the spatial variability in the influence of C fluxes and albedo on changes in GWP.

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1. Introduction

Human alterations to land use and land cover are important drivers of global environmental change by invoking large perturbations to the terrestrial carbon (C) cycle and surface energy dynamics (Barnes and Roy, 2010; Georgescu et al., 2014; Houghton et al., 2012). Fortunately, global rates of deforestation have stabilized or are declining (Keenan et al., 2015), however, human settlements are rapidly expanding (Seto et al., 2012) and becoming the new face of land use and land cover change (LULCC). The spatial extent of many of the world's largest cities increased 16-fold during the 20th century (Angel et al., 2011) due to rapid population growth and migration of people from rural areas to cities (Grimm et al., 2008). Urban lands now cover ~3% of the global land area (Liu et al., 2014) and are expanding twice as fast as their populations (Angel et al., 2010, 2011). The extent of urban land cover is expected to triple between 2000 and 2030 (Seto et al., 2012), but declining densities of metropolitan areas may expedite growth rates (Angel et al., 2011). The United States (U.S.) has the largest urban extent of any country (112,000 km^2; Angel et al., 2011) and developed land is its most rapidly expanding biome (Sleeter et al., 2013; USDA, 2013). While urban areas have more than doubled between 1950 and 2000, the extent of exurban development (i.e., just beyond the urban fringe) has increased five-fold (Brown et al., 2005). Following these trends, by 2025 developed land is projected to comprise 9.2% of the contiguous U.S., an area nearly the size of Texas (Alig et al., 2004).

Expansion of human settlements is of growing concern because it results in complex patterns of intermixed vegetated and impervious surface areas and ecosystem fragmentation that introduce large, and often permanent, shifts in the biophysical composition of the global landscape. For example, human settlements can convert landscapes from a sink to source of C to the atmosphere by reducing biogenic C uptake and increasing fossil fuel combustion (Imhoff et al., 2004; Hutyra et al., 2011). Similarly, shifts in albedo following expansion of human settlements can alter the energy balance and climate at local, regional and even continental scales (Menon et al., 2010; Oke, 1973).

Human settlements are increasingly being recognized as an important part of the terrestrial C cycle (Churkina et al., 2010; Hutyra et al., 2014; Pataki et al., 2006), but their effects can be difficult to quantify due to the heterogeneous nature of development and associated impacts on biogenic C fluxes. In mesic environments, expansion of human settlement tends to reduce vegetation biomass and C storage. For example, Raciti et al. (2014) found that biomass C in the City of Boston, Massachusetts was 75% lower than an intact forest, but there was considerable spatial variation within the city driven by variations in development intensity. Similar effects of development on C storage were observed in the Seattle, Washington where biomass declined over time and with proximity to the urban core (Hutyra et al., 2011). In contrast, expansion of human settlements in arid environments can increase C storage when native vegetation is replaced with trees and lawns (e.g., Golubiewski, 2006).

Growing conditions are also often altered as a landscape is developed. Cultural practices such as watering (Mini et al., 2014) and fertilization as well as increased nitrogen deposition (Rao et al., 2014), CO_2 fertilization (Idso et al., 1998) and a longer growing season associated with the urban heat island effect (Yang et al., 2013) can potentially increase productivity of vegetation in developed landscapes. In contrast, elevated exposure to pollutants such as ozone can reduce productivity (Gregg et al., 2003). While little is known about how these factors interact to affect tree growth, recent work suggests that the productivity of trees can double when the surrounding land is developed (Briber et al., 2015). Across large geographic areas, vegetation biomass and C assimilation generally decrease with increasing development intensity (Zhao et al., 2012) and urbanization has been estimated to reduce U.S. national annual net primary productivity (NPP) by 1.6%, compared to the pre-urban era (Imhoff et al., 2004).

As human settlements expand, vegetation and other natural land covers are replaced with roads, sidewalks, buildings and parking lots. This process creates a mosaic of surfaces with differing albedo characteristics, which in aggregate, can change the surface energy dynamics of the landscape (e.g., Georgescu et al., 2014; Sleeter et al., 2013). For example, LULCC between 1973 and 2000 was estimated to reduce the albedo of the contiguous U.S. (Barnes and Roy, 2010). However, albedo values across the continuum of surfaces that exist within a developed landscape can vary by 50% (Barnes and Roy, 2010; Sailor, 1995). As a result, expansion of human settlements can warm or cool the local or regional climate depending on the relative abundance and distribution of different surfaces (Kong et al., 2014).

While the expansion of human settlements clearly affects the terrestrial C cycle and surface energy budgets at local to global scales, most of the developed land that will exist by 2050 has yet to be built. While this may mean that the largest impacts of development are yet to come, there is also the opportunity for scientists, policymakers and land managers to shape the form and magnitude of these impacts (Georgescu et al., 2014; Lawler et al., 2014). In recent years, several studies have improved our understanding of the potential impacts of future human settlement expansion on U.S. land covers across a range of development trajectories obtained from the IPCC Special Report on Emissions Scenarios (Bierwagen et al., 2010; Nakicenovic and Swart, 2000; Sohl et al., 2012, 2014), econometric models (e.g., Radeloff et al., 2012), projections of cropland demand (e.g., Lawler et al., 2014) and recent patterns of development (e.g., Thompson et al., 2011). However, these studies did not explicitly project changes in C fluxes, surface energy dynamics and global warming potential (GWP) associated with expansion of human settlements. Seto et al. (2012) projected changes in the global extent of urban areas, but primarily focused on the C implications of urbanization in tropical regions.

The objectives of this study are to a) present an approach to quantifying the effects of projected changes in human settlements on terrestrial C storage and fluxes, and surface albedo at a spatial resolution sufficient to aid in policy decision making at the municipal scale, and b) assess the GWP of these biophysical changes to the landscape. We integrate nationally available datasets on land cover and forest biometrics with the U.S. Environmental Protection Agency's (EPA) Integrated Climate and Land Use Scenarios (ICLUS) model (Bierwagen et al., 2010). The state of Massachusetts located in the northeastern U.S. is used as an initial case study to develop this approach because of the existence of high quality data sets, rapid rates of development in recent history and its high proportions of both forested and developed land covers, Massachusetts is simultaneously the eighth most forested and third most densely populated state in the U.S.

2. Methods

2.1. Study area and land use and land cover history

Massachusetts has a population of 6.7 million people and five cities with more than 100,000 people with Boston being the most densely populated city (5151 people km^{-2}; U.S. Census Bureau, 2015). Massachusetts has a humid, continental climate characterized by warm summers and cold, snowy winters with seasonal temperature ranges generally increasing from east to west. The capital city, Boston is located on the east coast of the state has mean monthly temperatures of −1.7 °C in January and 23.3 °C in July and receives approximately 1100 mm of precipitation, evenly distributed throughout the year (National Climatic Data Center, 2014). Mixed-deciduous temperate forest is the dominant natural land cover type.

Massachusetts, similar to most of the eastern U.S., was nearly entirely forest prior to European colonization (ca. 1600), but rapid agricultural expansion reduced forest cover to <30% of the land area by the middle of the 19th century (Foster and Aber, 2004; Jeon et al., 2014; Fig. 1). Agricultural abandonment allowed forest cover to increase during the