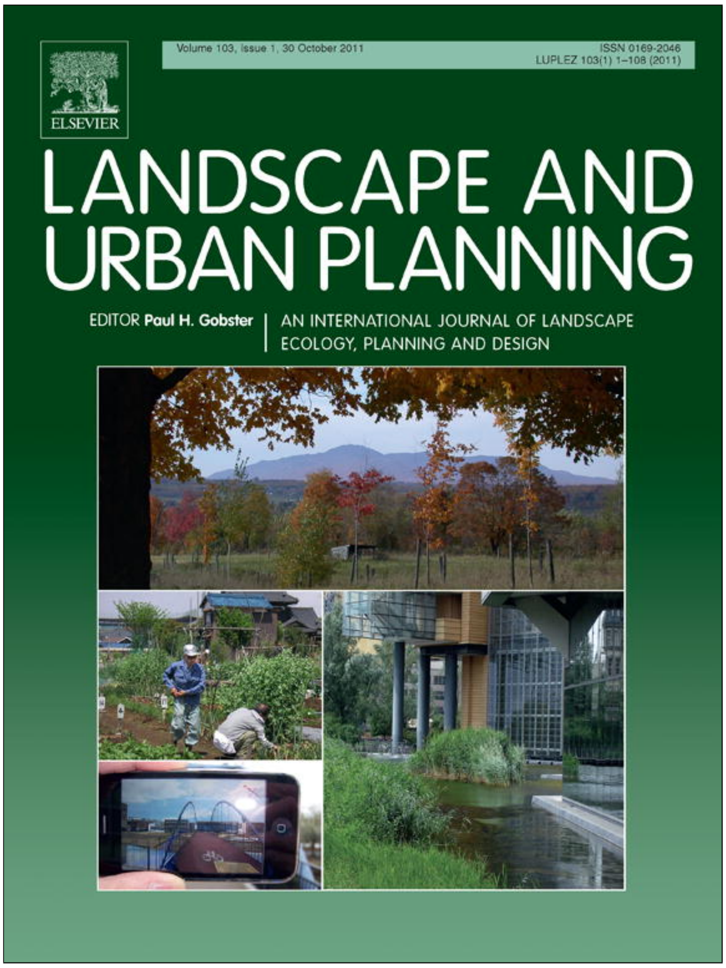
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Carbon consequences of land cover change and expansion of urban lands: A case study in the Seattle metropolitan region

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ABSTRACT

Understanding the role humans play in modifying ecosystems through changing land cover is central to addressing our current and emerging environmental challenges. In particular, the consequences of urban growth and land cover change on terrestrial carbon budgets is a growing issue for our rapidly urbanizing planet. Using the lowland Seattle Statistical Metropolitan Area (MSA) region as a case study, this paper explores the consequences of the past land cover changes on vegetative carbon stocks with a combination of direct field measurements and a time series of remote sensing data. Between 1986 and 2007, the amount of urban land cover within the lowland Seattle MSA more than doubled, from 1316 km^2 to 2798 km^2, respectively. Virtually all of the urban expansion was at the expense of forests with the forested area declining from 4472 km^2 in 1986 to 2878 km^2 in 2007. The annual mean rate of urban land cover expansion was $1 \pm 0.6\%$ year^{-1}. We estimate that the impact of these regional land cover changes on aboveground carbon stocks was an average loss of 1.2 Mg C ha^{-1} yr^{-1} in vegetative carbon stocks. These carbon losses from urban expansion correspond to nearly 15% of the lowland regional fossil fuel emissions making it an important, albeit typically overlooked, term in regional carbon emissions budgets. As we plan for future urban growth and strive for more ecologically sustainable cities, it is critical that we understand the past patterns and consequences of urban development to inform future land development and conservation strategies.

1. Introduction

One of the most influential factors in human-induced global environmental change over the last two hundred years has been the transformation of land and resource use associated with urbanization and expanding low density development (Ojima, Galvin, & Turner, 1994; Seto & Shepherd, 2009; Turner, Lambin, & Reenberg, 2007). Around the globe, rates of land cover change and losses in terrestrial carbon stores are expected to increase significantly in the coming decades as population continues to grow (Foley et al., 2005; Montgomery, 2008; Ramankutty & Foley, 1999; Theobald, 2005). Currently, over 50% of the population lives in urban areas, but by 2050 United Nations estimates suggest that 70% of the global population will be urbanites (UNFPA, 2007). Within North America, estimates of the urban lands vary between 0.2 and 4.9% of total land area, but mapping changes and projecting future growth of urban land cover has proved to be particularly difficult due to the heterogeneity associated with urban landscapes (Schneider, Friedl, & Potere, 2009). The process of urban expansion results in complex patterns of intermixed high- and low-density built-up areas and a fragmentation of the natural landscape. Urbanization affects ecological processes both directly – by simplifying and fragmenting habitat in human-dominated systems – and indirectly – by changing the biophysical attributes of the landscape that result in a variety of interrelated local and global impacts (Alberti & Marzluff, 2004).

The creation and expansion of cities and urban areas is typically associated with significant carbon emissions through the removal of vegetation, the addition of impervious surfaces, and increases in local fossil fuel usage. However, in arid regions, urbanization may actually increase vegetative cover due to human plantings and additions of water (McHale et al., 2009). Nowak, Walton, Dwyer, Kaya, and Myeong (2005) found that urban land cover in the conterminous United States increased by 23% in the 1990s

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while the population increased by 13%, suggesting increasing per capita land areas and urban sprawl. The challenges and consequences of sprawling patterns of urban development have been extensively examined in the literature and are reviewed by Ewing (1997) and Brueckner (2000). Broadly, sprawl development patterns are characterized by low-density housing and strip-style commercial developments that rely heavily on private automobile transportation (Ewing, 1997). As a result, such patterns have been shown to simultaneously increase per capita pollution levels (Gonzalez, 2005) and the consumption of resources (Ewing, 1997; Grimm et al., 2008), while significantly altering native land covers through conversion, fragmentation, perforation, and appropriation (Alberti & Marzluff, 2004; Medley, McDonnell, & Pickett, 1995).

Due to the concentration of people, vehicles, and industrial activities, urban and urbanizing areas are a major source of global CO_2 emissions (Svierejeva-Hopins, Schellnhuber, & Pomaz, 2004). Currently, urban areas are estimated to consume 67% of global energy and emit 71% of CO_2 worldwide (IEA, 2008). However, estimates of fossil fuel emissions at the county level for the United States tell a complicated story for urban regions. For example, when contrasting New York, Los Angeles, and King (Seattle, WA area) Counties, per capita emissions are estimated at 2.54, 2.21, and 2.83 $\mathrm{Mg\,C\,yr^{-1}}$, respectively, but per area emissions are 453.3, 17.5, and 8.34 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$, respectively, because the concentration of populations and land areas are very different in these urban regions (Gurney et al., 2009). Further, varying quantities of the industrial and commercial activities (e.g. electricity generation) that support these cities are located within these urban counties themselves, making direct emissions comparisons particularly challenging and error prone (Kennedy, Cuddigy, & Engel-Yan, 2007).

Beyond high concentrations of human populations and impervious surface areas, urban and urbanizing areas also contain vegetation that can store varying quantities of carbon (Hutyra, Yoon, & Alberti, 2011; Nowak & Crane, 2002) and impact ecosystem functions (Kaye, Groffman, Grimm, Baker, & Pouyat, 2006). Among other impacts, changes in urban vegetation affect local climates (Oke, Crowther, McNaughton, Monteith, & Gardiner, 1989) and the heating/cooling needs of buildings (McPherson & Simpson, 1999; McPherson, Simpson, Xiao, & Wu, 2011). Urban vegetation is also an important natural amenity (Geoghegan, Wainger, & Bockstael, 1997). Nonetheless, urban vegetation is typically not included in national vegetation inventories, as it falls outside common classification schemes and the spatial resolution of remotely sensed imagery used to create many land cover maps (Pataki et al., 2007; USDA, 2008). Decreases in vegetative cover, due to expansion and intensification of urban land areas, have the potential to result in significant carbon losses from the terrestrial biosphere.

During the last decades we have learned a great deal about the interactions between urbanization and ecosystem functions (Grimm et al., 2008; Liu et al., 2007; Pickett et al., 2011), however, there are few studies that have systematically examined the spatio-temporal interplay of land cover change in urbanizing regions with the specific aim to explore the carbon impacts of expanding urban areas (Alberti & Hutyra, 2009; Cathcart, Kline, Delaney, & Tilton, 2007; Heath, Smith, Skog, Nowak, & Woodall, 2011). With the objective of empirically estimating the carbon impacts of urbanization, this paper examines land cover changes in the rapidly developing Seattle, WA urban region between 1986 and 2007. As we plan for future urban growth and strive for more ecologically sustainable cities, it is critical that we understand the past patterns and consequences of urban development to inform our future land development, management, and conservation strategies.

2. Methods

2.1. Site description and development history

Situated in the middle of the Puget Sound region, the greater Seattle, Washington area has spatially abrupt gradients of moisture, nutrients, temperature, and elevation that have resulted in a wide diversity of terrestrial ecosystems and shaped the patterns of land development (Kruckeberg, 1995). The Seattle climate is temperate, with an annual mean temperature of 10.9 °C and ∼942 mm of precipitation $\mathrm{year^{-1}}$ (NOAA, 2004). The vegetation is largely temperate, moist forest. The west slope of the Cascade Mountains is dominated by coniferous tree species: Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*). The lowland Puget Sound forests include a similar coniferous species assemblage and deciduous species such as bigleaf maple (*Acer macrophyllum*), black cottonwood (*Populus trichocarpa*), and red alder (*Alnus rubra*). Approximately half of the three counties comprising the Seattle Metropolitan Statistical Area (MSA, see definition below) are high elevation (>500 m), with the region containing the Cascade Mountain range and Mt. Rainer National Park. For this analysis, the spatial focus is the lowland (<500 m elevation) MSA where nearly all of the urban development is currently occurring.

Native American groups have inhabited the Seattle region since the last glacial period, but the founding of Seattle is typically dated to 1851. The City of Seattle was incorporated in 1865 and had an estimated population of 350 people (Mighetto & Montgomery, 2002). In 1889, nearly the entire Seattle business district was destroyed in the 'Great Seattle Fire'. In the years following the fires, the city was quickly rebuilt and the population doubled from pre-fire numbers to approximately 40,000 inhabitants (Davies, 2001). In the 20th century the Seattle area became a center for timber, aircraft, and technology industries. In response to concerns about suburban sprawl and the adverse environmental consequences of development, the Washington State legislature passed the Growth Management Act (GMA; Chapter 36.70A RCW) in 1990, which required counties and cities to prepare and adopt 20-year comprehensive land use plans and establish urban growth boundaries restricting areas for new urban development.

The Seattle-Tacoma-Bellevue Metropolitan Statistical Area (MSA) is located between the Puget Sound to the west and the Cascade Mountain range to the east (Fig. 1). Within the Seattle MSA (16,333 $\mathrm{km^2}$, including King, Pierce, and Snohomish counties) are lakes, rivers, an inland sea, national forests, and much of the Mount Rainer National Park. The Seattle MSA includes several large business districts and currently accounts for more than 50% of Washington State's population. According to the US Census, Seattle has consistently ranked as the 20th to 25th largest urban center in the United States over the last decades. For the last several decades, the Seattle region has experienced sustained population growth in excess of 1% $\mathrm{yr^{-1}}$, with most of the development occurring outside the Seattle city limits (Fig. 2). The Seattle MSA is projected to grow 32.4% between 2005 and 2030 (WOFM, 2007).

2.2. Data sources and data integration

To assess trends in population, land cover, and terrestrial carbon changes in the Seattle MSA, we integrated US census data, a time series of Landsat-based land cover maps (Alberti, Weeks, & Coe, 2004; Hepinstall-Cymerman, Coe, & Alberti, 2009), a digital elevation model, and field measurements of aboveground live biomass (Hutyra et al., 2011). Most of the historical population data were obtained from the US Census for the Seattle MSA region, with population estimates for 1880 and 1890 originating from Sale (1978).

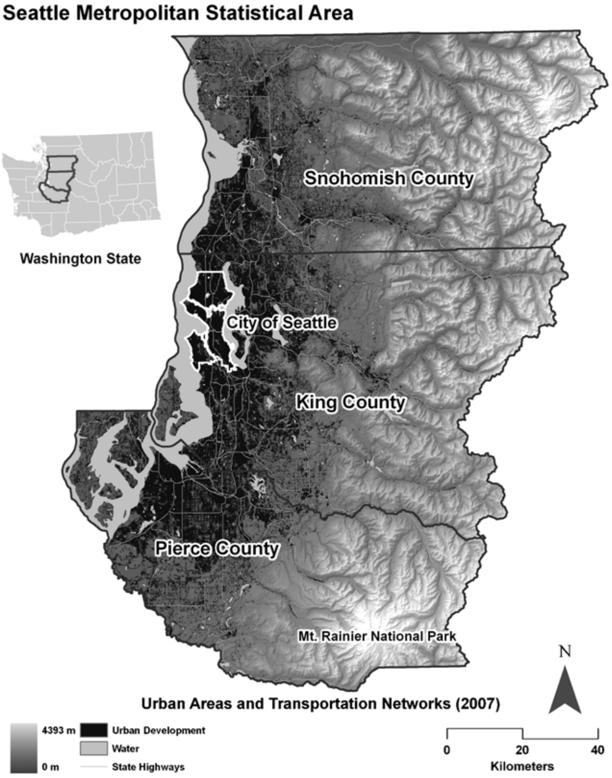

Fig. 1. Digital elevation model of the Seattle Metropolitan Statistical Area (MSA; Snohomish, King, and Pierce counties) with the City of Seattle, 2007 urban areas (including low, medium, and high urban land cover classes), and the major roadways overlaid.

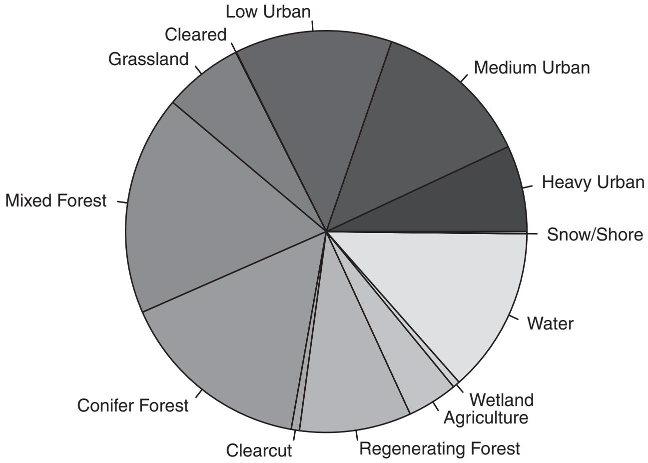

Fig. 3. Fractional distribution of 2007 lowland land cover in the Seattle Metropolitan Statistical Area, including a full breakdown of the non-focal ('other') land cover classes.

Land cover data were obtained from the University of Washington, Urban Ecology Research Laboratory (Hepinstall-Cymerman et al., 2009). Remote sensing images from the Landsat Thematic Mapper and the Enhanced Thematic Mapper were used to classify the land cover at a 30 m resolution across the Seattle region for the years 1986, 1991, 1995, 1999, 2002, and 2007 (see Hepinstall-Cymerman et al., 2009 for full methodological details and data processing methods). In brief, supervised and unsupervised classifications were combined with spectral un-mixing techniques to interpret multi-season Landsat imagery (leaf-on and leaf-off) for each time stamp to differentiate the land cover into 14 distinct classes. For this analysis, the original 14 land cover classes were aggregated into 6 cover classes including heavy urban (>80% impervious surface area (ISA)), medium urban (50–80% ISA), light urban (20–50% ISA), mixed forest, conifer forest, and 'other'. The 'other' land cover class was consolidated to include classes that typically contain only small amounts of aboveground biomass and were not field surveyed as part of the Hutyra et al. (2011) Seattle biomass analysis. The aggregated 'other' land cover classes included cleared for development, grass/grasslands, agriculture, clearcut forest, regenerating forest, non-forested wetlands, open water, shoreline, and snow/bare rock/ice cover classes (Fig. 3).

Nearly all of the Seattle MSA area fell within a single Landsat scene and the land cover maps are based on this single scene. The northeastern portion of Snohomish County was missing from the Landsat scene and was excluded from this land cover change analysis. All land cover changes are reported on a per hectare or percentage basis of the available data. The impact of the missing Snohomish County data on the reported results was very small since most of the missing data is high elevation land in the Cascade Mountains that would not have been included in this analysis due to the elevation; 2.2% of the lowland MSA land area was missing due to the spatial extent of the Landsat scene and the classified land cover data.

Field sampling to measure aboveground carbon stocks within vegetation was conducted in 2009 by Hutyra et al. (2011). Measurements were made on both publicly and privately held lands, to assess aboveground terrestrial carbon stocks as a function of land cover and distance from the Seattle central urban core. A total of 154 fixed area plots (706 m^2 each) were established along three transects radiating eastward from the Seattle urban core (UTM zone 10N: 5495181E, 52737651N) sampling across 5 different classes of

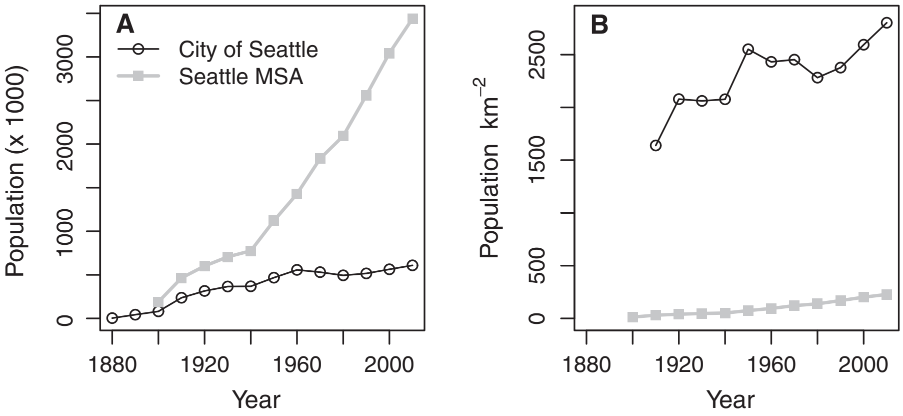

Fig. 2. Time series of total population (A) and population density (B) for the City of Seattle and the Seattle Metropolitan Statistical Area between 1880 and 2010.

land cover: heavy urban, medium urban, light urban, mixed forest, and coniferous forest (see Hutyra et al., 2011 for a full methodological description). Field measurements were limited to areas below 500 m to eliminate the variance in biomass associated with elevation change. All extrapolation of the Hutyra et al. (2011) results applied here continue to be limited to the lowland areas and the 5 cover classes measured in the field.

2.3. Land cover change estimates

To assess the carbon consequences of the increasing urban land areas and decreasing forest areas, we applied the aboveground carbon stock values estimated in Hutyra et al. (2011) to the time series of remote sensing-based, classified land cover data. Since the patterns of vegetation change over time within a given land cover class were not known (e.g. growth, mortality, etc.), the carbon stocks within the five cover classes field surveyed by Hutyra et al. (2011) were assumed to be static based on the 2009 Seattle field surveys. The 'other' land cover category was assumed to have 0 Mg C ha^{-1} in live vegetation in our change analysis.

All parenthetically reported errors in the land cover and biomass change patterns are 95% confidence intervals based on the different annualized rates of change for the five time-intervals of the 21-year time series. Error estimates include inter-annual variability in the rates of land cover change, but do not include allometric or biomass scaling errors. Overall accuracy in the satellite land cover classification errors were not directly included, but Hepinstall-Cymerman et al. (2009) found a very good overall observed agreement for our major classes, ranging from 79.5 to 89% with kappa values between 0.69 and 0.84.

2.4. Vulcan emissions estimates

We compared annualized carbon losses from land cover change with the 2002 Vulcan fossil fuel emissions estimates (Gurney et al., 2009; http://www.purdue.edu/eas/carbon/vulcan/research.html) using both the estimated total county emissions for the three counties within the Seattle MSA and the 10 km high-resolution annual emissions product. To estimate lowland emissions we derived a scaling factor by evenly distributing the total emissions within a 10 km Vulcan pixel down to a 30 m resolution (to match the land cover data and elevation data) and determined a ratio of the lowland to total MSA emissions. The missing part of Snohomish County was included in the scaling to produce the most accurate estimate possible for the whole Seattle MSA area and the lowlands. The Vulcan lowland scaling factor was then multiplied by the total county Vulcan emissions to estimate the lowland emissions. This scaling was applied to minimize the spatial misallocation of emissions associated with our downscaling and the impact of partial 10 km Vulcan pixels within our study area. This emissions factor downscaling approach was adapted because standard methods are not optimal for excluding the high elevation, largely unpopulated areas. Both total county and downscaled lowland emissions are reported. For consistency with the Vulcan methodologies, water areas were not masked/removed in the Vulcan scaling.

3. Results

3.1. Land cover changes

During the study interval, land cover across the Seattle MSA changed significantly, but the rates of change were not constant over time or between the various cover classes (Table 1 and Fig. 4). Broadly, between 1986 and 2007 the urban lands (sum of heavy, medium, and light urban cover classes) expanded from 17.3 to 37.3% and forest cover (including mixed and coniferous forest)

Table 1
Estimated aboveground biomass and land cover distributions within the lowland (<500 m elevation) Seattle MSA between 1986 and 2007. The average aboveground C stocks are based on field measurements by Hutyra et al. (2011) and the distribution of land cover in 2007 within the lowland MSA.

	Average aboveground C stocks (Mg C ha^{-1}) in live vegetation in 2009	1986 area (ha) and percent lowland MSA area	1991 area (ha) and percent lowland MSA area	1995 area (ha) and percent lowland MSA area	1999 area (ha) and percent lowland MSA area	2002 area (ha) and percent lowland MSA area	2007 area (ha) and percent lowland MSA area
High urban	2 ± 2.1	22,402 ha (2.9%)	28,027 ha (3.7%)	33,280 ha (4.4%)	41,978 ha (5.5%)	53,689 ha (7.1%)	60,012 ha (8.0%)
Medium urban	13 ± 11.6	56,018 ha (7.4%)	74,963 ha (9.9%)	83,967 ha (11.1%)	80,861 ha (10.7%)	94,600 ha (12.5%)	110,359 ha (14.7%)
Low urban	38 ± 36.4	53,229 ha (7.0%)	75,641 ha (10.0%)	91,940 ha (12.1%)	110,806 ha (14.6%)	121,087 ha (16.0%)	109,463 ha (14.6%)
Mixed forest	99 ± 41.6	229,983 ha (30.3%)	226,616 ha (29.9%)	215,240 ha (28.4%)	196,754 ha (26.0%)	168,129 ha (22.2%)	152,863 ha (20.4%)
Conifer forest	183 ± 61.9	217,215 ha (28.6%)	166,931 ha (22.0%)	142,942 ha (18.9%)	147,752 ha (19.5%)	154,403 ha (20.4%)	134,959 ha (18.0%)
Other land[a]	0[b]	180,585 ha (23.8%)	184,933 ha (24.4%)	190,310 ha (25.1%)	179,836 ha (23.7%)	165,231 ha (21.8%)	180,934 ha (24.2%)

[a] Other land cover classes include regenerating forest, clearcut, cleared for development, wetland, shoreline, agriculture, grassland, and snow/bare rock). Water was excluded.

[b] For conservative change estimates 'other' land cover classes were assumed to hold 0 Mg C ha^{-1}.

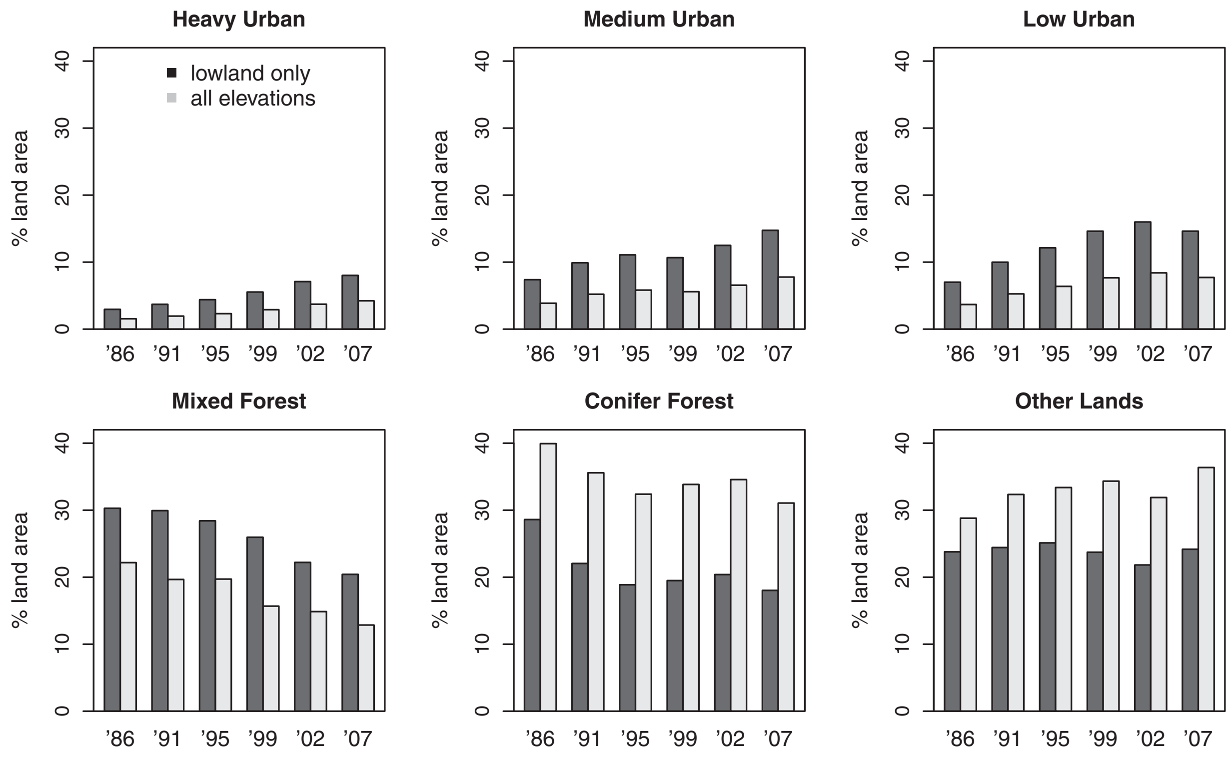

Fig. 4. Land cover fractions in 1986, 1991, 1995, 1999, 2002, and 2007 for the full Seattle Metropolitan Statistical Area (MSA) and the lowland (below 500 m elevation) portions of the MSA, gray and black bars, respectively.

declined from 58.9 to 38.4% of the lowland Seattle MSA. There were no large changes in the 'other' land cover classes; Fig. 3 shows the fractional breakdown of the original 14 land cover classes as observed in 2007. Similar patterns of land cover change were observed within the lowlands (<500 m elevation) and within the full MSA (all elevations), with 99.9% of the urban land cover being located within the lowland areas (Figs. 1 and 4).

Fig. 5 presents a map of forest cover in 2007 and urban areas in 1986, with two periods of new urban expansion being overlaid for 1986–1995 and 1995–2007. The locations of the new urban pixels highlights an infilling of the urban areas, an urban elongation following the north-south corridor of the Interstate-5 highway, and an outward progression of new urban development away from the Seattle urban core. Most of the new urban lands were located outside the Seattle city limits (Figs. 1 and 5). The patterns of urban land cover change and related forest cover trajectories observed between the two time periods (1986–1995 and 1995–2007) showed trends of both urban densification within the Seattle core and sprawl at the periphery. The overall increase in developed land and decline of forest cover is consistent between the two time periods but the degree of urban intensification varied across time steps (Figs. 4 and 5). A decline in median urban cover between 1995 and 1999 corresponded to a simultaneous increase in urban densification (increase in high urban cover) and decentralization of the urban structure (increase in low urban cover). Between 2002 and 2007 there was a small decrease in low urban cover and a large increase in medium urban cover.

The mean annual rate of urban land cover expansion within the lowland Seattle MSA between 1986 and 2007, was 1 ± 0.6% year^{-1}, with an associated mean population density change of 1.3% year^{-1} (from 138 to 227 people km^{-2} between 1980 and 2010; Fig. 2). Within the Seattle city limits (based on the 2000 municipal boundary), urban land cover increased from 81.9 to 92.1% between 1986 and 2007 (Table 2). Over the same period, the mean annual rate of urban land cover expansion within the Seattle city limits was 0.5 ± 0.44% year^{-1}, while the city population density grew by 0.6% year^{-1} (from 2282 to 2802 people km^{-2} between 1980 and 2010, respectively). Overall, land area in urban classes increased more rapidly by area and by percentage of new urban land cover outside the Seattle city limits. Note the Seattle city limits have been increasing over time through annexation, growing from 144.7 km^2 in 1910 to 217.2 km^2 in 2000, affecting population density estimates; the land area of the Seattle MSA has been constant over time.

3.2. *Temporal changes in aboveground carbon stocks as estimated by land cover change*

Building upon the field measurements of aboveground live biomass reported in Hutyra et al. (2011), we applied their mean biomass estimates to the time series of lowland land cover to assess the biomass stock changes associated with regional land cover changes between 1986 and 2007 (Table 1 and Fig. 6). The mean aboveground live biomass for the lowland areas by cover class, based on the 2002 distribution of land cover within the three field survey segments (0–7.5 km, 7.5–30 km, >30 km within the lowland MSA), varied from 2 ± 1.9 Mg C ha^{-1} for heavy urban to 183 ± 60 Mg C ha^{-1} for conifer forests (Hutyra et al., 2011).

Table 2
Urban land cover area within the city of Seattle (~212.5 km^2) and across the lowland Seattle MSA (~14,416 km^2). The values for the city of Seattle are calculated using a fixed area reflecting the city boundary in 2000.

	City of Seattle only	Full lowland Seattle MSA
1986	174.1 km^2 (81.9%)	1316 km^2 (17.3%)
1991	185.0 km^2 (87.0%)	1786 km^2 (23.6%)
1995	189.2 km^2 (89.0%)	2092 km^2 (27.6%)
1999	191.6 km^2 (90.2%)	2336 km^2 (30.8%)
2002	195.0 km^2 (91.8%)	2694 km^2 (35.6%)
2007	195.7 km^2 (92.1%)	2798 km^2 (37.4%)

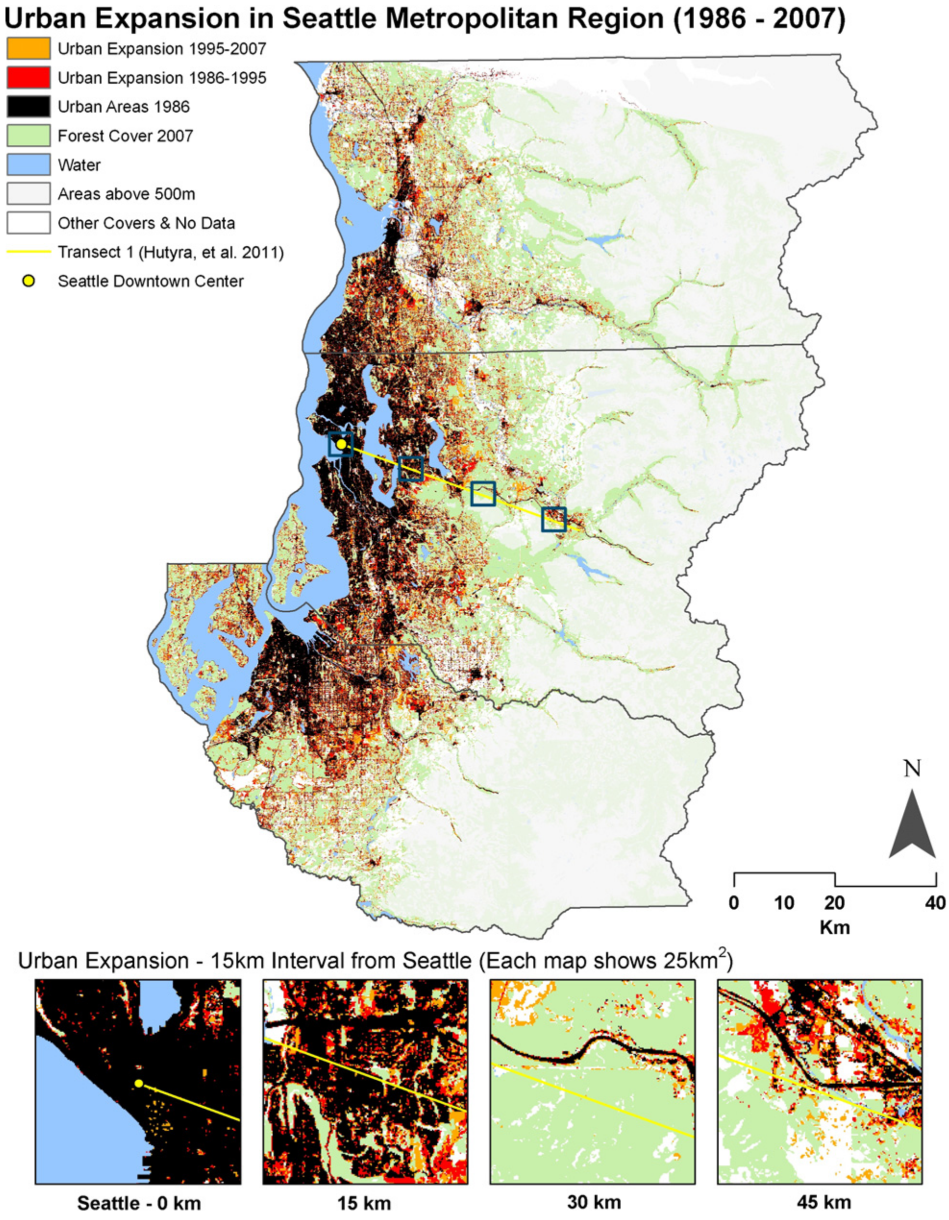

Fig. 5. Patterns of urban expansion in the Seattle Metropolitan Statistical Area between 1986 and 2007. Urban areas in 1986 are overlaid with new urban development in 1986–1995 and 1995–2007. One of the field transect lines from Hutyra et al. (2011) is overlaid with four 25 km^2 segments to highlight the changes in development patterns with distance from the urban center.

Within a 7.5 km radius of the Seattle urban core, the average aboveground live biomass showed the smallest absolute change, declining from 17.6 to 13.1 Mg C ha^{-1} between 2007 and 1986, with a mean annualized change of −0.2 Mg C ha^{-1} yr^{-1}(range from −0.6 to +0.02; Fig. 6). The biomass changes in this area were low because the population density was high and the amount of intact vegetation was low; there was little available forest land for development. Further, the urban intensification occurring in the Seattle urban core only resulted in a small change in the amount of biomass since the shift from low or medium urban to high urban represents a much smaller vegetative carbon loss than the transition of forest cover to urban lands. Within 7.5 km of the urban core, the medium urban cover class emerged as storing the most total biomass because it was more abundant than the low urban or forest land cover classes and was found to hold more biomass per unit area than high urban.

As the distance from the Seattle urban core increased, the fraction of biomass held within forest covers increased because both the proportion of forested land cover increased and the Seattle area forests hold more biomass per unit area than urban land covers (Fig. 6). Between a radial distance of 7.5 and 30 km from the Seattle urban core, the average amount of biomass decreased from 63.1 to 47.8 Mg C ha^{-1} with marked declines in the conifer and mixed forest biomass over the 21-year period; the change in this spatial sector was −0.8 Mg C ha^{-1} yr^{-1} (range from −1.7 to −0.02). Beyond a 30 km radius from the Seattle urban core, the mean aboveground biomass declined from 92.6 Mg C ha^{-1} in 1986 to 65.5 Mg C ha^{-1} in 2007 with mean annual change of 1.2 Mg C ha^{-1} yr^{-1} (range from −2.3 to −0.1). Integrating across the full lowland Seattle MSA, biomass declined from 86.1 to 60.9 Mg C ha^{-1} from 1986 to 2007, respectively, with the fraction of biomass stored within forested land cover classes decreasing from 96 to 87%, due to the increase in the urban land cover fraction. The average annual decline in vegetative carbon stocks associated with land cover change for the entire MSA was 1.2 Mg C ha^{-1} yr^{-1} (annualized range of loss from 2.2 to 0.1 across the given time intervals).

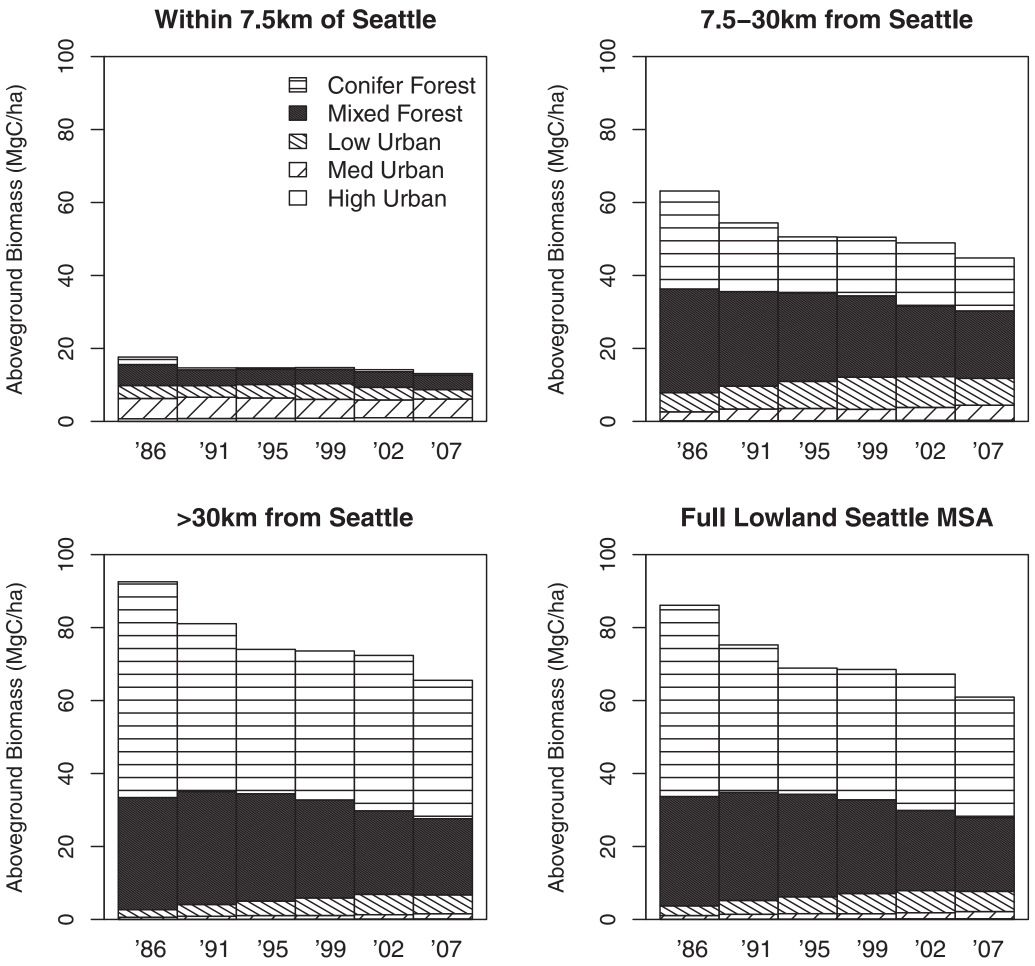

Fig. 6. Changes in the mean aboveground live biomass across the lowland Seattle MSA as a function of distance from the Seattle central urban core. The 7.5 km and 30 km spatial extents are highlighted in Fig. 7.

Between 1986 and 2007, the change in the spatial distribution of land cover below 500 m clearly showed the urban expansion and resulting changes in aboveground biomass for the full lowland Seattle MSA (Fig. 7). While the map of biomass change is dominated by carbon losses, there were isolated pixels and several patches in the urban periphery that increased in biomass through shifts in the land cover classes and forest protections; 16% (118,776 ha) of the lowland MSA area showed a change in land cover that is associated with increasing biomass, primarily associated with re-growth of previously harvested forestlands.

3.3. *Fossil fuel emissions estimate*

The 2002 county-specific fossil fuel carbon emissions estimated by Vulcan (Gurney et al., 2009) are reported in Table 3. We estimated the lowland to overall MSA fossil fuel emissions fraction to be 0.94 for the Seattle MSA. 2002 fossil fuel emissions per unit area for the full and for the lowland portions of the MSA were 4.9 and 8.4 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$, respectively (Table 3). Note, that the lowland land areas (ha) for the Vulcan and land cover change estimates reported in this study were slightly different due to the treatment of water areas (specified in Table 3). Within the Seattle MSA, King County had the highest population density and emissions (both total and per unit area).

4. Discussion

Terrestrial ecosystems are an important and dynamic component of the global carbon cycle. In recent decades, terrestrial ecosystems have absorbed approximately 25% of the carbon emitted to the atmosphere by human activities (Canadell et al., 2007). The global fossil fuel and cement emissions are estimated to be $5.4 \pm 0.3\,\mathrm{Gt\,C\,yr^{-1}}$ with an additional land use change carbon flux to the atmosphere of 1.7 (0.6 to 2.5) $\mathrm{Gt\,C\,yr^{-1}}$ (Denman et al., 2007). Approximately 90% of the land use change carbon flux is attributable to deforestation (Denman et al., 2007). While most of the global emphasis to reduce deforestation and its associated carbon emissions has justifiably been centered in the tropics and in developing counties (e.g. The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries; REDD), we have shown here that urbanization is also an important driver of land use change and can result in significant emissions in temperate regions alike.

Urban areas are hotspots for CO_2 emissions through a combination of direct local emissions (e.g. automobiles and industrial activities) and demand by the urban populations for energy and products. The process of urbanization also involves the conversion of land from other uses (e.g. forest or agriculture) that modify the ecosystem services provided by the land (Kareiva, Watts, McDonald, & Boucher, 2007). In non-arid regions, the amount of vegetation in urbanizing areas is typically reduced and then

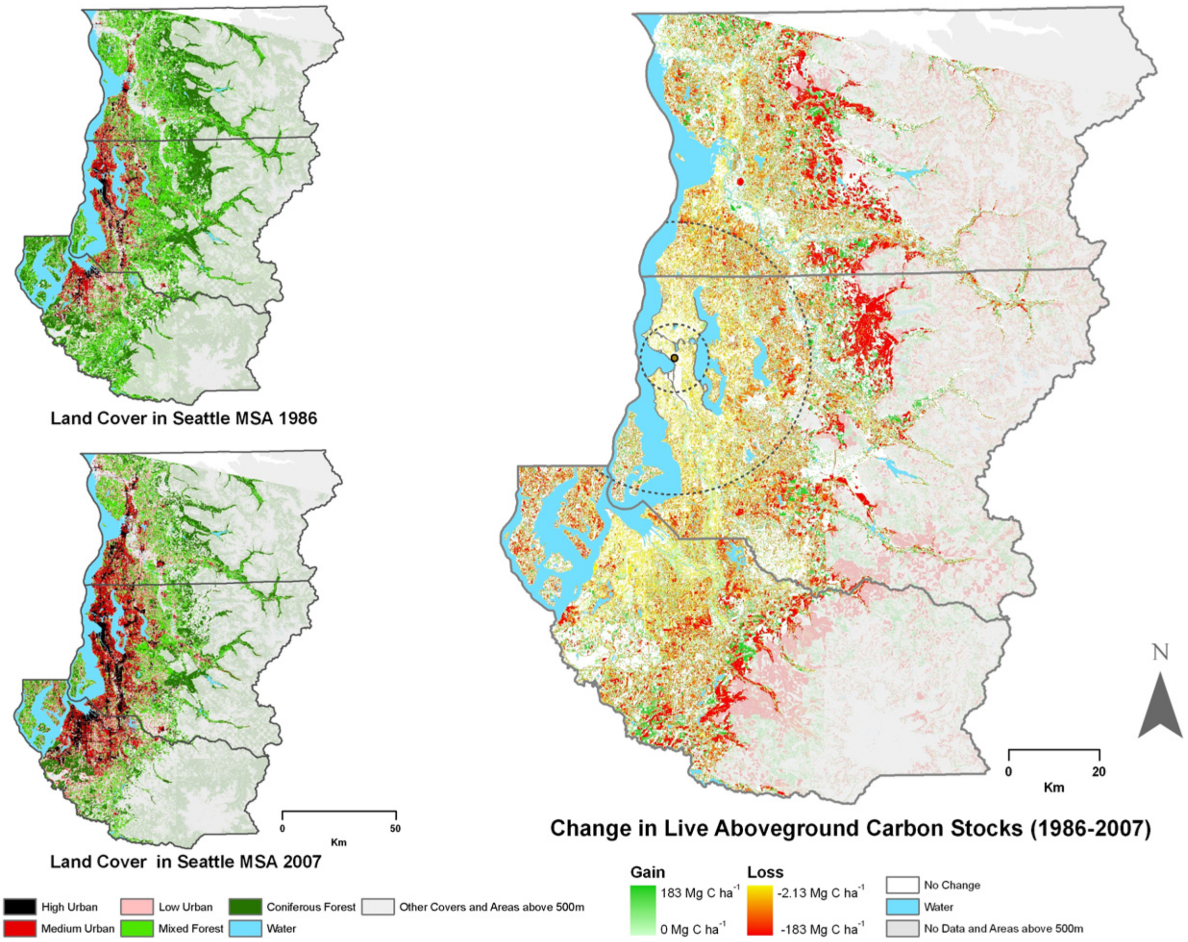

Fig. 7. Map of the lowland Seattle Metropolitan Statistical Area land cover in 1986 and 2007, with the change in total estimated aboveground carbon stocks between 1986 and 2007. Radial rings around the Seattle urban core indicate a 7.5 and 30 km distance.

replaced with impervious surfaces resulting in a loss of both stored carbon and a reduction in the future terrestrial uptake potential by the land.

While being home to over 3.4 million people, the lowland Seattle MSA area also holds very high carbon stores within its vegetation. Hutyra et al. (2011) estimated the mean aboveground live biomass across the Seattle urbanizing region was 89 ± 22 Mg C ha^{-1} in 2002 (including both urban and forest areas), with an average of 140 ± 40 Mg C ha^{-1} stored within urbanizing area forests and 18 ± 13.7 Mg C ha^{-1} stored within urban land covers. Biomass within the Seattle MSA was substantially larger than values reported by Nowak and Crane (2002) for 10 U.S. cities (25.1 Mg C ha^{-1} aboveground biomass within urban forest land only) and than the average of 53.5 Mg C ha^{-1} reported by Birdsey and Heath (1995) for all U.S. forests. The combination of aboveground biomass measurements and remotely sensed data presented here indicate that the lowland Seattle metropolitan region has been losing 1.2 Mg C ha^{-1} yr^{-1} in aboveground biomass through urbanization and land cover change. Despite the large carbon stocks and the rapid biomass changes, most of the lowland MSA area is not included in forest inventories because it is classified as urban.

The average annualized carbon losses due to aboveground vegetation reductions associated with land cover change correspond to nearly 15% of the lowland MSA fossil fuel emissions (Table 3). Carbon accounting for land cover changes is notoriously difficult (Houghton, 1999), but these challenges do not negate our critical need for estimates of this type for various regions across the globe. Estimates of carbon losses from land cover change are very sensitive to the accounting methods and their underlying assumptions; estimates such as these require methodological transparency to avoid potential biases in comparisons.

The Vulcan fossil fuel emissions and the land cover change carbon losses (Table 3) are not strictly comparable because the fossil fuel emission are immediately transferred from fuel to the atmosphere, while not all the carbon associated with land cover changed is immediately transferred to the atmosphere. A portion of the harvested wood will likely be stored in longer-lived product pools such as furniture and building materials. In an analysis of Pacific Northwest forests, Cathcart et al. (2007) estimated that 35% of the pre-harvest forest carbon biomass will continue to be stored in forest products. The carbon loss rates estimated here did not account for the carbon stored in long-lived wood products (a term which would reduce the estimated annual mean loss rate), but we assumed that the carbon loss from urbanization of non-forest land covers was 0 Mg C ha^{-1} (an assumption which reduced the estimated emissions). The influence of forest product carbon storage would most significantly impact the areas that are transitioning between conifer or mixed forest to an urban land covers, since that wood is likely to be sold. In the case of intensification of the urban cover (e.g. a transition from low to medium urban), the carbon storage within forest products would likely represent a much smaller fraction of the carbon pool since it is less likely to be commercially processed due to the low volume of biomass removed.

The ‘other’ land cover category was assumed to have 0 Mg C ha^{-1} in live vegetation in our change analysis. While this assumption

Table 3
Annualized emissions estimates for the full Seattle MSA and the lowland (<500 m elevation) MSA region based on Vulcan reported fossil fuel emissions (Gurney et al., 2009) and this land cover change analysis (average annual changes from 1986 to 2007).

	2002 Vulcan total fossil fuel emissions (Mg C)	Population (2000 census)	Total area (ha)	Lowland area [non-water land area] (ha)	Lowland fossil fuel emission fraction	2002 Vulcan fossil fuel emissions (Mg C ha^{-1} yr^{-1})	2002 Vulcan lowland fossil fuel emissions (Mg C ha^{-1} yr^{-1})	Biomass carbon loss due to lowland land cover change (Mg C yr^{-1})	Biomass carbon loss due to lowland (non-water) land cover change (Mg C ha^{-1} yr^{-1})
King County	4,984,666	1,737,034	597,210	343,562 [295,304]	0.94	8.4	13.6	327,037	1.1
Snohomish County	1,512,242	606,024	568,491	292,039 [243,897[a]]	0.93	2.7	4.8	329,389	1.4
Pierce County	1,487,995	700,820	467,365	253,774 [217,947]	0.94	3.2	5.5	283,576	1.3
Seattle MSA	7,984,903	3,043,878	1,633,066	889,376 (757,148[a])	0.94	4.9	8.4	940,001	1.2

[a] For consistency, the non-water, lowland Snohomish County land area used for calculating the land cover related carbon losses excludes the northeast section missing from the classified land cover time series.

is an underestimate since there is likely to be some live vegetation larger than 5 cm in diameter at breast height (threshold used in the Hutyra et al., 2011 analysis) within this 'other' category, the values can reasonably be expected to be very low (e.g. agricultural cover classes are dominated by crops not trees) and the net effect of this assumption is a more conservative estimate of carbon losses since the dominant direction of land cover change was toward urban covers. The live biomass carbon pools were also assumed to be constant within a given class over time, this assumption likely resulted in a small underestimate of carbon losses based on the rates of change (less removals) reported by the USDA Forest Inventory Analysis (FIA) for *Pseudotsuga menziesii* in the Pacific Northwest (USDA, 2008). Finally, the land cover carbon estimates changes did not include losses from coarse woody debris pools (mean additional carbon stock of 12 ± 4 Mg C ha^{-1} in the lowland Central Puget Sound area; Hutyra et al., 2011) or soil carbon pools; the inclusion of these terms would substantially increase the land cover change estimated emissions. Overall, the 1.2 Mg C ha^{-1} yr^{-1} carbon loss rate is a first order, conservative estimate of the carbon consequences of vegetative losses from land cover change in the Seattle MSA during this 21-year period.

The average carbon loss estimates from land cover change per hectare per year between 1986 and 2007 correspond to nearly 15% of the Vulcan 2002 lowland regional fossil fuel emissions (Table 3), highlighting that vegetation changes in urbanizing area can be a substantial term in regional carbon budgets. While we cannot allocate the proportion of the land cover change emissions that were directly and solely attributable to urban expansion, it is clear, based on the spatial patterns of urban growth and the large regional reductions in commercial logging, that urban development is a dominant factor driving these regional land cover conversions.

5. Conclusions and implications

The results from this study provide new estimates and insights as to the impacts of urban expansion and the associated land cover changes on terrestrial carbon stocks. While land cover change-driven emissions will vary significantly in magnitude by biome and settlement patterns, we can expect that carbon losses will be typical for non-arid regions.

Urban areas currently cover only a small fraction of the globe, but the emissions and changes in local ecosystem structure and function have disproportionate impacts on global environmental changes (Grimm et al., 2008; Kareiva et al., 2007). If recent growth trends continue, the expansion of urban areas will markedly outpace the growth in urban populations, making urban land use change and the carbon dynamics therein ever more important for the global carbon cycle (Brown, Johnson, Loveland, & Theobald, 2005; Churkina, Brown, & Keoleian, 2010; Hutyra et al., 2011). Estimates of land cover change related emissions reported here are likely to be some of the largest we will see within the continental United States because the Seattle area vegetation holds particularly large biomass stocks, but these results highlight urbanization as an important driver of deforestation and land cover change. Further, much of the projected urban growth worldwide is forecasted to take place in the developing tropics (e.g. the population of Southeast Asia is expected to shift from 41.8 to 65.4% urban by 2050; UN, 2009) where the land cover change emissions from urbanization will likely be large due to the high current forest biomass carbon pools.

Cities, states, and nations are taking significant steps to reduce their carbon emissions through changes such as transitioning to hybrid municipal vehicle fleets and improving building energy efficiency. While these types of changes are clearly valuable and a key step in reducing local emissions, the maintenance and enhancement of vegetative cover in both urban and rural areas could have a very significant and local impact on net carbon emissions in non-arid regions. Financial mechanisms to support forest conservation, afforestation, and forestry offsets are currently being formalized through programs such as the Clean Development Mechanism of the Kyoto Protocol, the Regional Greenhouse Gas Initiative, the American Carbon Registry, and the Climate Action Reserve, but there are still significant complexities in the implementation of projects and much of the current emphasis is on improved forest management and avoided commercial deforestation.

We are reporting very high carbon losses due to past land cover changes in the Seattle region, but in recent years Washington State has become a leader in urban growth management regulation. State municipalities and other governing bodies have been implementing growth management activities (i.e., comprehensive development plans) derived from the Washington State Growth Management Act and we are hopeful that some of the past patterns of land cover change will shift going forward with more spatially concentrated urban growth.

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