Increasing Gross Primary Production (GPP) in the Urbanizing Landscapes of Southeastern Michigan

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Abstract

In order to understand the impact of urbanizing landscapes on regional gross primary production (GPP), we analyzed changes in land-cover and annual GPP over an urban-rural gradient in ten Southeastern Michigan counties between 1991 and 1999. Landsat and AVHRR remote sensing data and biophysical parameters corresponding to three major land-cover types (i.e., built-up, tree, and crop/grass) were used to estimate the annual GPP synthesized during the growing season of 1991 and 1999. According to the numbers of households reported by the U.S. Census in 1990 and 2000, the area settled at urban (>1 housing unit acre^{-1}), suburban (0.1 to 1 housing units acre^{-1}), and exurban (0.025 to 0.1 housing units acre^{-1}) densities expanded, while the area settled at rural (<0.025 housing units acre^{-1}) densities reduced. GPP in this urbanizing area, however, was found to increase from 1991 to 1999. Increasing annual GPP was attributed mainly to a region-wide increase in tree cover in 1999. In addition, the estimated annual GPP and its changes between 1991 and 1999 were found to be spatially heterogeneous. The exurban category (including constantly exurban and exurban converted from rural) was associated with the highest annual GPP as well as an intensified increase in GPP. Our study indicates that low-density exurban development, characterized by large proportions of vegetation, can be more productive in the form of GPP than the agricultural land it replaces. Therefore, low-density development of agricultural areas in U.S. Midwest, comprising significant fractions of highly productive tree and grass species, may not degrade, but enhance, the regional CO_2 uptake from the atmosphere.

Introduction

Data from the U.S. Census has illustrated that much of the Eastern U.S. is undergoing significant deconcentration of population, leading to increased prevalence of low- to medium-density settlement across broad areas that were previously rural (Theobald, 2001). Nationwide, the area of land settled at densities of one house per 1 to 40 acres (i.e., suburban and exurban) increased about 500 percent from 1950 to 2000 (Brown *et al*., 2005). This rate of suburban and exurban sprawl was shown to be more rapid in areas outside, but in proximity to, metropolitan regions. Based on these documented demographic changes, we identified two important environmental questions: (a) how does the density of residential development influence land-cover change?, and (b) what are the impacts on primary production? Because residential development is affecting such large areas, i.e., low-density development occupied 15 times the area of dense urban settlements (Brown *et al*., 2005), the answers to these questions could have significant consequences for regional and global carbon accounting.

In order to answer the two questions listed above, we analyzed changes in land-cover and gross primary production (GPP) in ten Southeastern Michigan counties where suburban and exurban sprawl intensified between 1991 and 1999. Our approaches included: (a) mapping land-cover distribution and estimating annual GPP in each year, using Landsat and AVHRR remote sensing data; (b) deriving the pixel-wise changes in land-cover proportions and annual GPP between 1991 and 1999; and (c) characterizing land-cover proportions and annual GPP by development-density categories (i.e., urban, suburban, exurban, and rural) and their changes by development-direction classes (i.e., conversions between any two development-density categories). We also examined sensitivity of the estimated GPP and its changes to different land-cover datasets and estimates of biophysical parameters. Our hypothesis was that low-density exurban development may not reduce annual GPP over the region as a whole at the scale of Census block group, because GPP that is reduced by increasing impervious surface and declining agriculture may be compensated through increasing areas of planted, re-growing, or maturing woody vegetation.

Background

Characterizing Development Density

In our study, we used housing-unit density instead of population density as the indicator of development density, because population counts ignore the effects of changes in household sizes (i.e., given a fixed population total, a smaller average household size implies more residential dwelling units, leading to a larger settlement area). Housing-unit density at the scale of Census block group equals the number of housing units divided by the land area of the block group. Housing-unit density does not directly take into account commercial and industrial land-uses.

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Based on Census housing-unit density, four categories of development density were defined, following Theobald (2001) and including: urban (>1 housing unit acre^{-1}, or less than 1 acre per housing unit), suburban (0.1 to 1 housing units acre^{-1}, or 1 to 10 acres per housing unit), exurban (0.025 to 0.1 housing units acre^{-1}, or 10 to 40 acres per housing unit), and rural (<0.025 housing units acre^{-1}, or more than 40 acres per housing unit). New development associated with increasing housing-unit density may result in conversion from a lower to a higher development-density category (i.e., rural to exurban, exurban to suburban, and suburban to urban, etc).

Evaluating Primary Production

Two measures of primary production are widely used to describe ecosystem exchange of carbon between plants and the atmosphere. Gross primary production (GPP) is the total amount of carbon that is fixed by plants during the process of photosynthesis, and net primary production (NPP) is GPP less autotrophic respiration (i.e., plant respiration).

We used GPP as the measurement in this study for two reasons. First, compared to NPP, GPP can be more directly calculated from remotely sensed vegetation indices, given the more direct link of photosynthesis to plant's reflectance of shortwave radiation (e.g., Sellers, 1987). Second, estimates of GPP may have less uncertainty than NPP at local to regional scales. Uncertainties of estimation may increase when remote sensing measurements are coupled with ecological models that are required to calculate NPP (Zhao *et al.*, 2006). These models, in addition to estimating additional biophysical parameters, normally involve use of climate and/or soil data at degraded spatial resolutions. The increased uncertainty may prevent detection of real changes in productivity at the local to regional scale, such as those we aim to detect in our study.

GPP is difficult to measure directly but can be estimated with reflectance data collected by remote sensing instruments, based on light-use efficiency theory (Running *et al.*, 2000; Turner *et al.*, 2003). Light-use efficiency (LUE or ε) is defined as the ratio of total carbon uptake by green vegetation through photosynthesis (i.e., GPP) to the absorbed photosynthetically active radiation (APAR). It is the energy-to-carbon conversion efficiency and varies among different species and communities. APAR can be calculated if incident solar radiation and reflectance of the intercepted vegetation canopy are known, and used to estimate GPP provided reasonable estimates of LUE are available.

Data and Methods

Study Area

Our study region covers the Detroit-Ann Arbor-Flint consolidated metropolitan statistical area (CMSA), a ten-county region consisting of urban, suburban, exurban, and rural settlement densities (Figure 1). Previous research has documented relatively rapid development in the suburban and exurban parts of this region, despite declines within the cities of Detroit and Flint from the late 1950s to the present (McCarthy, 1997; Theobald, 2001; Brown *et al.*, 2005). The 1990 and 2000 U.S. Census of population showed that the city of Detroit lost 8 percent of its residents, while the population of the CMSA increased 17 percent. According to household data of the Census, the total number of housing units declined 9 percent in city of Detroit, while it increased 21 percent in the CMSA. These opposing trends indicate continuing decentralization of the city, declining household sizes, and new development in suburban, exurban, and rural areas in 1990s.

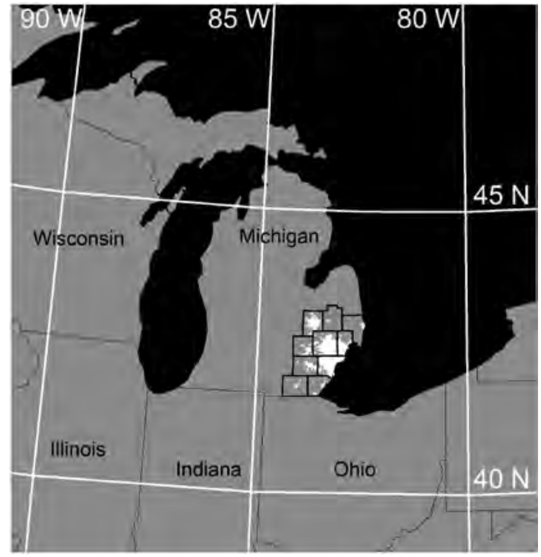

Figure 1. Study area covered ten Southeastern Michigan counties shown in thick black outlines, with the Detroit-Ann Arbor-Flint consolidated metropolitan statistical area displayed in white color.

Land-cover Data

Landsat TM/ETM+ data collected during summers of 1991 and 1999 were geometrically registered and converted to six feature bands per dataset, which included Normalized Difference Vegetation Index (NDVI), Tasseled Cap brightness, Tasseled Cap wetness, ratio of band 4/band 7, texture of band 5, and texture of band 4/band 3. These six feature bands and a road-density map were used in unsupervised classification to generate 80 land-cover clusters in 1991 and 1999, respectively. We labeled and combined the clusters into five land-cover types, i.e., built-up, tree, crop/grass, water, and other (Table 1). Land-cover accuracy was assessed using randomly sampled 90 m $\times$ 90 m blocks of reference data that were scanned from aerial photographs at a resolution of 2 meters. The overall accuracies of the Landsat classification were 76.84 percent in 1991 and 82.27 percent in 1999. The users' accuracies were 71.48 percent (79.35 percent) for built-up, 70.59 percent (79.43 percent) for tree, and 81.71 percent (85.44 percent) for crop/grass in 1991 (1999). To calculate GPP at 1 km resolution, binary presence/absence maps were derived for built-up, tree, and crop/grass, respectively, in each year. Classes of water and other were not included in our calculations, as they were assumed to be relatively constant with respect to GPP. These 30-meter resolution binary land-cover data were then aggregated to create 1 km resolution grids to describe the percentage of built-up, tree, and crop/grass within each 1 km $\times$ 1 km cell, respectively.

To evaluate the sensitivity of our analysis to alternative maps of land-cover, we compared the results calculated using the land-cover data described above with estimates calculated using two other independent land-cover datasets that were also compiled from Landsat imagery. The datasets from 1992 National Land Cover Data (NLCD; Vogelmann *et al.*, 2001) and 1999 to 2000 Michigan Integrated Forest Monitoring Assessment and Prescription (IFMAP) (Michigan Department of Natural Resources, 2003) replaced our 1991 and 1999 land-cover classification, respectively. Land-cover

Table 1. Definition of Land-Cover Types

Land-cover Type	Description
Built-Up	Combines the high- and low-density residential/commercial lands. The former is composed of impervious surface in a large fraction (over 70 percent of cover) and scattered vegetation. The latter is a mixture of impervious surface in a smaller fraction (30 to 70 percent of cover) and increasing proportion of vegetation.
Tree	Combines broadleaf deciduous trees, needleleaf coniferous trees, and woody shrubs. Dominant tree species include oak, hickory, maple, beech, elm, ash, and cottonwood. According to the 1993 and 2001 Forest Inventory and Analysis (FIA) data, coniferous species occupied only 2 to 2.5 percent of the total forested area in the Southeastern Michigan region.
Crop/Grass	Combines agricultural farmlands and grassy fields. Dominant crops (by area) are corn, soybean, and hay (alfalfa). Over 90 percent of the cropland is rain-fed, according to the 2002 USDA Census of Agriculture.
Water	Combines rivers, lakes, and ponds.
Other	Combines wetlands, parks, and golf courses.

classes of the two datasets were grouped to match our definition of built-up, tree, and crop/grass before performing the comparative calculations of annual GPP.

Development Density

We mapped development-density categories in 1990 and 2000 using housing-unit counts from the 1990 and 2000 U.S. Census of households. Census block-group boundaries for both Census dates came from the Michigan Geographic Framework (MGF, 2005), which was created based on the 1994 Census Topologically Integrated Geographic Encoding and Referencing (TIGER) line files and improved with the U.S. Geological Survey (USGS) 1:12 000 Digital Ortho Quarter Quad (DOQQ) aerial photography. To derive the total land area that may be used in development, we removed water from the total area of each block group by using masks extracted from our 1991 and 1999 Landsat land-cover classification. We then calculated housing-unit density as the ratio of housing units to land area for each Census block group. Based on housing-unit density, Census block groups were classified into four development-density categories consisting of urban, suburban, exurban, and rural, as previously defined.

Annual GPP

We calculated GPP using methods based on light-use efficiency theory. Daily GPP (GPP_d) equals the absorbed photosynthetically active radiation (APAR) multiplied by the energy-to-carbon conversion efficiency (i.e., LUE or ε), where APAR can be estimated from the incident radiation in photosynthetic wavelengths (PAR) multiplied by the fraction of PAR that is absorbed by plants (fPAR; Running *et al.*, 2004). We calculated GPP_d of each land-cover type ($GPP_{d,lc}$; g C m^{-2} day^{-1}) for each 1 km × 1 km cell by:

$$GPP_{d,lc} = \%_{lc} \times \varepsilon_{lc} \times (PAR_d \times fPAR_{d,lc}) \quad (1)$$

where $\%_{lc}$ is the proportion of a given land-cover (i.e., built-up, tree, or crop/grass) in each 1 km × 1 km cell, ε_{lc} is the LUE of the land-cover type (g C MJ^{-1}), PAR_d is the daily incident PAR (MJ m^{-2} day^{-1}), and $fPAR_{d,lc}$ is the fraction of PAR_d absorbed by the land-cover type.

We used 1.8 and 2.2 g C MJ^{-1} for ε_{lc} of tree and crop/grass, respectively, based on the growing-season averaged LUE modeled by Turner *et al.* (2003) for ecosystems comparable to our land-cover types, i.e., mixed conifer/deciduous forest (42.5°N, 72°W) and maize-dominated agricultural field (40°N, 88°W). For built-up, we estimated ε_{lc} to be 0.88 g C MJ^{-1} based on the estimated fractions of impervious surface (56 percent), trees (22 percent), and grass (22 percent) within our built-up areas. According to our land-cover classification, the high- and low-density residential/commercial types occupied approximately 30 percent and 70 percent of the built-up area, respectively. Given an estimated 70 to 100 percent and 30 to 70 percent of impervious surface for the high- and low-density residential/commercial types, respectively, the average fraction of vegetated cover was estimated at 44 percent for the built-up type. Assuming an even distribution of trees and grass on the vegetated surfaces and that $\varepsilon_{impervious}$ equals zero, ε_{lc} of built-up was set to 0.22 times the sum of ε_{tree} and $\varepsilon_{crop/grass}$, i.e., 0.88 g C MJ^{-1}.

The land-cover proportion ($\%_{lc}$) used in Equation 1 came from our binary land-cover data aggregated to 1 km resolution. PAR_d was calculated based on monthly mean downward shortwave radiation (J sec^{-1} m^{-2}; NASA Data Assimilation Office, 1993) multiplied by the scalar 0.45 (i.e., the photosynthetically active proportion of the total incident shortwave electromagnetic radiation) and 24 hours in units of seconds. $fPAR_{d,lc}$ was calculated based on the biweekly 1-kilometer AVHRR NDVI (USGS EROS Data Center EDC, 1989), using an empirical MODIS NDVI-fPAR look-up table (LUT; Knyazikhin *et al.*, 1999). The AVHRR NDVI in the range 0.12 to 0.62 was first multiplied by 1.45 (Huete *et al.*, 2002) to convert it into units of MODIS NDVI, for the purpose of applying the MODIS-based LUT to estimate fPAR. We used NDVI-fPAR LUT values of broadleaf forest and broadleaf crop for our tree and crop/grass types, respectively. The LUT values for the built-up type was estimated with values for tree and crop/grass types, based on fractions of impervious surface (56 percent), trees (22 percent), and grass (22 percent) within our built-up type.

Once $GPP_{d,lc}$ was estimated for each land-cover type in each pixel according to Equation 1, the total daily GPP (GPP_d; g C m^{-2} day^{-1}) was derived by summing $GPP_{d,lc}$ values across land-cover types found within each pixel. Because this daily total was an estimate based on the maximum AVHRR NDVI over each 14-day time period, the accumulated daily GPP in each of the two-week time spans was derived by multiplying GPP_d by 14 days. We summed the accumulated biweekly GPP across the 11 two-week periods from early May to early October (during this period the average minimum daily temperature was 10°C and above), to estimate the pixel-wise growing-season GPP (GPP_{gs}; g C m^{-2} year^{-1}) as:

$$GPP_{gs} = \sum_{tp=1}^{11} (14 \times \sum_{lc=1}^{3} GPP_{d,lc}) \quad (2)$$

where lc is the three land-cover types, and tp is the 11 two-week time periods corresponding to the biweekly AVHRR NDVI data over the growing season.

To evaluate the sensitivity of our estimation of GPP_{gs} to alternative LUE values, we calculated the growing-season GPP based on five additional combinations of ε_{lc} (Table 2). In total, we developed six representative estimates using (a) the average ε_{lc}, (b) the maximum ε_{lc}, (c) the minimum ε_{lc}, (d) ε_{lc} assuming the least productive tree and most productive crop/grass, (e) ε_{lc} assuming the most productive tree and least productive crop/grass documented by Turner *et al.*, (2003);

Table 2. Light-use Efficiency (LUE, g C MJ^{-1}) Used in the Estimation of Daily GPP by Land-cover Types. LUE of Built-up was Approximated from Values of Tree and Crop/Grass, which Came from Turner *et al.* (2003) for Case a through e, and Running *et al.* (2000) for Case f

Case #	Built-Up	Tree	Crop/Grass
a	0.880	1.800	2.200
b	1.120	2.600	2.900
c	0.550	1.000	1.500
d	0.858	1.000	2.900
e	0.902	2.600	1.500
f	0.362	1.044	0.604

and (f) ε_{lc} used in Biome-BGC (BioGeochemical Cycles) that was applied to the global estimation of GPP and NPP with MODIS data (Running *et al.*, 2000).

Changes in Land-cover and GPP by Changes in Development Density

We compared maps of the 1990 and 2000 development-density categories to derive changes in development density, which we referred to as development-direction classes. Sixteen possible development directions consist of the constant classes (i.e., no conversions between development-density categories, including constantly urban, constantly suburban, constantly exurban, and constantly rural), urbanized classes (i.e., conversions from a lower to a higher development-density category, including urban converted from suburban, urban converted from exurban, urban converted from rural, suburban converted from exurban, suburban converted from rural, and exurban converted from rural), and ruralized classes (i.e., conversions from a higher to a lower development-density category, including rural converted from exurban, rural converted from suburban, rural converted from urban, exurban converted from suburban, exurban converted from urban, and suburban converted from urban).

If a class occupied less than 1 percent of the total study area, we combined it with other rare classes to create an "other conversion" class. The class of other conversion consisted of nine minor conversion directions and accounted for less than 3 percent of the total land area. The major development-direction classes included constantly urban (U), constantly suburban (S), constantly exurban (E), constantly rural (R), urban converted from suburban (UfromS), suburban converted from exurban (SfromE), and exurban converted from rural (EfromR). We calculated changes in land-cover proportions and GPP_{gs} for each Census block group, and then calculated the area-weighted average of these changes by eight development-direction classes (i.e., the seven major development-direction classes and the class of other conversion).

Results

Among the five land-cover types identified from the 30-meter Landsat imagery (Table 3), crop/grass dominated Southeastern Michigan by area, although it declined from 52 percent in 1991 to 49 percent in 1999. Tree was the second dominant land-cover type and increased from 20 percent in 1991 to 23 percent in 1999. Area of built-up occupied about 20 percent of the total study area and showed little change between 1991 and 1999. Water and other land-covers made up 8 percent of the total area with little change between 1991 and 1999.

Table 3. Area Proportion (Percent) of the Landsat Classified Land-cover Types in 1991 and 1999

	Built-Up	Tree	Crop/Grass	Water	Other
1991	20.3	19.9	52.0	2.4	5.4
1999	20.2	22.8	48.7	2.8	5.4

According to Census housing-unit density (Table 4), exurban was the dominant development-density category by area, followed by suburban and then urban (2000) or rural (1990). The total land area of the rural category decreased approximately 43 percent between 1990 and 2000, while the area of both urban and suburban categories increased about 15 to 16 percent. The exurban category increased slightly (0.6 percent by area). In both years, crop/grass was the dominant land-cover type in suburban, exurban, and rural categories, while built-up dominated the urban category. Proportion of tree by area was higher in the suburban and exurban categories than in the urban or rural category. Proportion of built-up by area was the lowest in the exurban and rural categories. In terms of changes in land-cover proportions, tree increased from 1991 to 1999, except in the rural category. Built-up declined, except in the urban category. Crop/grass declined in the urban and suburban categories, and increased slightly in the exurban and rural categories.

In both 1991 and 1999, the estimated annual growing-season GPP (GPP_{gs}) was highest in exurban, followed by rural, suburban, and urban (Table 4). Over the entire study area, the pixel-wise GPP_{gs} increased 3 percent (or 53 g C m^{-2} year^{-1}) on average, from 1,682 g C m^{-2} year^{-1} in 1991 to 1,735 g C m^{-2} year^{-1} in 1999. It increased as well in each of the development-density categories with different magnitude. The 1991 to 1999 increment was small for the urban category (39 g C m^{-2} year^{-1}), but large for the remaining categories (over 78 g C m^{-2} year^{-1}). Although estimates of GPP_{gs} varied with different assumptions for LUE values (Figure 2a), the annual GPP was consistently found to be (a) increasing between 1991 and 1999, and (b) highest in the exurban category and lowest in the urban category.

No major conversions from higher to lower development-density categories, i.e., ruralized classes, were found in our study area. Within the seven major development directions (Table 5), constant classes accounted for 79 percent of the total land area, while urbanized classes with conversions from lower to higher development-density categories occupied 18 percent of the total land area. Within the constant classes, the constantly exurban (E) and constantly suburban (S) classes dominated by area. Within the urbanized classes, suburban converting from exurban (SfromE) and exurban converting from rural (EfromR) dominated by area.

Increase in built-up proportion was high for suburban converted from exurban (SfromE) and urban converted from suburban (UfromS). Built-up proportion declined in the constantly rural (R), constantly exurban (E), and exurban converted from rural (EfromR) classes. All of the development-direction classes experienced increased tree cover, with the greatest expansion of tree cover occurring in constantly exurban (E) and exurban converted from rural (EfromR). Crop/grass declined in all development-direction classes except constantly rural (R).

The changes in annual GPP were positive except for the urban converted from suburban (UfromS) and constantly urban (U) classes. The constantly rural (R), exurban converted from rural (EfromR), and constantly exurban (E) classes were associated with the highest GPP increments from 1991 to 1999 (over 92 g C m^{-2} year^{-1}). The estimated magnitude of changes in annual GPP varied greatly depending on different sets of LUE values that were employed in

Table 4. Land-cover Proportions and Annual GPP (GPP_{gs}) by Development-Density Categories in 1991 and 1999. Values in Parentheses are Standard Error of Mean

Development Density	Year	Land Area (acres)*	% Built-Up	% Tree	% Crop/Grass	GPP_{gs} (g C m^{-2} $year^{-1}$)
Urban	1991	508656	66.4	9.2	21.1	674
			(0.36)	(0.15)	(0.24)	(5.85)
	1999	588362	67.3	13.2	14.7	713
			(0.38)	(0.20)	(0.20)	(6.41)
Suburban	1991	905279	21.4	24.5	45.5	1613
			(0.55)	(0.42)	(0.65)	(15.18)
	1999	1039136	19.1	28.0	44.0	1715
			(0.60)	(0.48)	(0.65)	(16.58)
Exurban	1991	1351029	9.1	24.8	61.3	1992
			(0.38)	(0.80)	(1.05)	(17.88)
	1999	1359776	5.2	28.1	63.0	2128
			(0.36)	(0.79)	(0.98)	(12.91)
Rural	1991	540742	8.5	18.0	70.2	1930
			(1.08)	(0.88)	(1.35)	(33.54)
	1999	306350	7.2	15.6	72.1	2008
			(1.86)	(0.88)	(2.03)	(49.83)

*Area in 1991 and 1999 was calculated based on the Census housing-unit density in 1990 and 2000, respectively.

Table 5. Changes in Land-cover Proportions and Annual GPP (GPP_{gs}) Between 1991 and 1999 by Development-Direction Classes

Development Direction*		Percent of Land Area (%)	Changes in Land-cover Proportions (%)			Changes in GPP_{gs} (g C m^{-2} $year^{-1}$)
			Built-Up	Tree	Crop/Grass	
Constant	U	14.0	4.7	2.7	–8.4	–29.91
	S	22.4	0.9	2.5	–4.0	16.67
	E	34.2	–2.8	4.4	–1.8	92.84
	R	8.4	–3.1	1.0	1.8	190.23
Urbanized	UfromS	3.0	10.6	1.3	–12.9	–154.67
	SfromE	7.8	21.6	3.3	–3.4	14.28
	EfromR	7.3	–2.4	3.7	–1.2	124.68
Other Conversion		3.0	1.8	2.1	–5.1	–12.76

*U: constantly urban, S: constantly suburban, E: constantly exurban, R: constantly rural, UfromS: urban converted from suburban, SfromE: suburban converted from exurban, EfromR: exurban converted from rural, Other Conversion: the aggregation of nine minor conversion directions occupying less than 3 percent of the total land area.

analysis (Figure 2b). However, despite variations in magnitude, the general pattern of enhanced increment in the constantly rural (R), exurban converted from rural (EfromR), and constantly exurban (E) classes were relatively stable for all assumptions of LUE values. Similarly, urban converted from suburban (UfromS) was always associated with the declining annual GPP.

Discussion

Increasing GPP in Southeastern Michigan

According to the Census housing-unit density in 1990 and 2000, Southeastern Michigan was characterized by increasing urbanization. Despite this trend towards more dense settlement patterns, our study found that the average regional GPP over the growing season increased rather than declined. Our investigation of changes in GPP by development-density categories (Table 4) and by development-direction classes (Table 5) showed that GPP increased in all categories and most classes, although more significantly in some than others. What has caused the increased GPP in this urbanizing environment? We examined the monthly average temperature and precipitation from the National Climatic Data Center Annual Climatological Summary during May through October in 1991 and 1999, and found no significantly different climate trends between the two years. Therefore, we suggest that the changes in GPP may be attributed to alterations in the incident solar radiation and land-cover proportions.

The temporal pattern of biweekly differences between 1991 and 1999 was very similar in the pixel-wise regional average of biweekly NDVI and estimated daily GPP (Figure 3). Given NDVI as an index of plant photosynthetic activity, Southeastern Michigan was greener in 1999 than in 1991 during the second half of the growing season. The increases in average NDVI during summer and autumn, 1999, may be attributed partially to the decline of incident solar radiation following the volcanic eruption of Mt. Pinatubo on 15 June 1991 (Ramachandran *et al.*, 2000). However, because no significant decline of NDVI was found in 35° to 45°N North America between 1991 and 1992 (Tucker *et al.*, 2001), this increase in NDVI in the later growing season of 1999 may be attributed alternatively to an increasing fraction of deciduous tree species that develop full crowns in summer. We suggest that this is confirmed by our findings of increasing tree cover over the study area (Table 5).

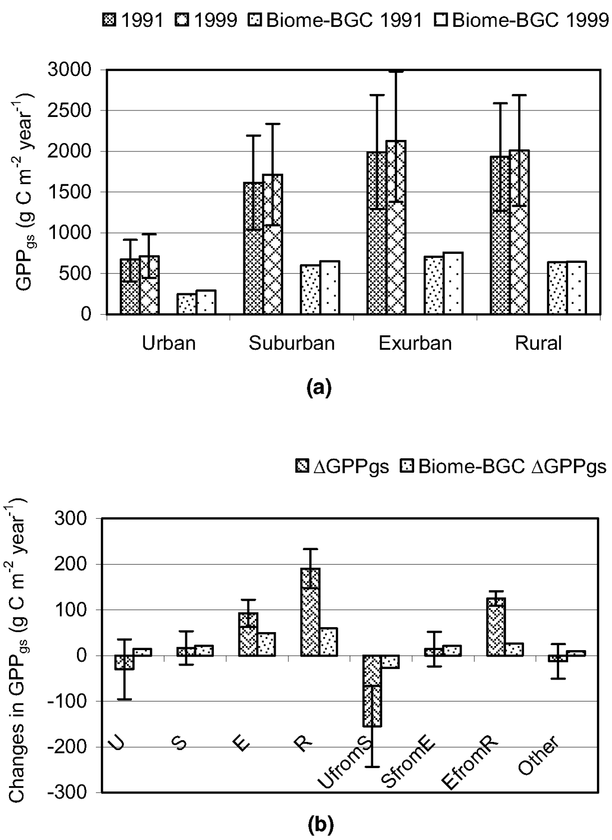

Figure 2. Annual GPP (GPP_{gs}, g C m^{-2} year^{-1}) by development-density categories (a) and its changes by development-direction classes (b). Error bars in (a) indicated the maximum and minimum annual GPP, which were calculated using the highest and lowest light-use efficiency (LUE) of tree and crop/grass adapted from Turner *et al*. (2003). Error bars in (b) indicated the maximum and minimum changes in annual GPP, which were calculated from the cross-combination of the highest and lowest LUE for tree and crop/grass adapted from Turner *et al*. (2003).

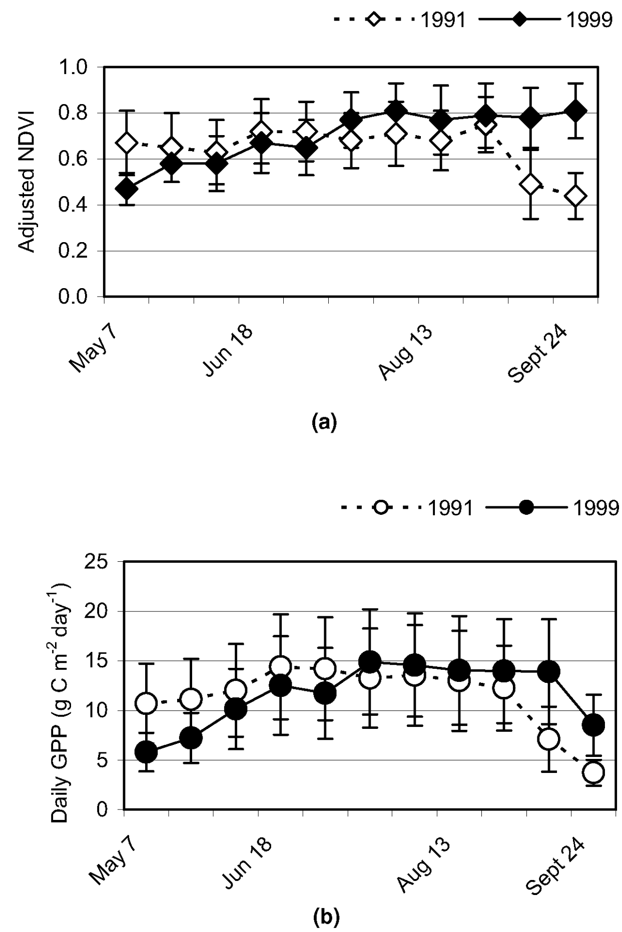

Figure 3. The pixel-wise regional average of (a) biweekly AVHRR NDVI (adjusted to units of MODIS NDVI) and (b) estimated daily GPP (GPP_d, g C m^{-2} day^{-1}) over the growing season between early May and early October. Dates on the *x*-axis corresponded to the starting date of each bi-weekly time period in 1991.

The expansion of tree cover in urban and suburban areas most likely results from tree and shrub cover filling in open urban lots plus continuing growth of existing urban trees. According to previous studies, the built infrastructure in the city of Detroit has been deteriorating since the 1960s due in part to the movement of the automobile and associated industries away from the city (McCarthy, 1997). Many old downtown neighborhoods, with the exception of scattered stable commercial and industrial areas, have been poorly maintained or abandoned with large areas of re-growing woody shrubs and trees (Ryznar and Wagner, 2001). Old suburbs might have experienced continuing growth and maturation of trees planted 30 to 60 years ago. The expansion of tree cover in the exurban areas was well documented in several concurrent land-cover/land-use change studies of the U.S. Upper Midwest (e.g., Bergen *et al*., 2005). In Southeastern Michigan, where there are significant development pressures, this appears to come from a combination of agricultural abandonment and the expansion or maturation of tree cover in low-density residential areas (including where tree crowns block housing structures underneath).

Among the four development-density categories, exurban was associated with the highest annual GPP in both 1991 and 1999. This result agrees with previous findings of the highest estimated NPP in exurban area in the U.S. Midwest region (Imhoff *et al*., 2004). Our study identified a mechanism for this fact in the form of a very high proportion of vegetated surface in exurban areas, i.e., 90 to 95 percent of the total land area in exurban was covered by tree and crop/grass. Although suburban contained the same proportion of tree cover, its built-up area was higher and crop/grass area was lower. Therefore, GPP in suburban areas was lower than exurban. GPP in urban areas was the lowest due to their large proportion of the built-up type. Depending on different values of LUE used in our analysis, rural was found either as productive as exurban or less productive than both exurban and suburban categories. This contradiction results from the large proportion (over 70 percent) of crop/grass in rural areas. Given a major contribution from the crop/grass type, the estimated GPP in rural areas is very sensitive to LUE used for crop/grass.

Although annual GPP increased on average throughout the entire region, the different development directions behaved somewhat differently. Despite variation across the different LUE assumptions, the estimated change in annual GPP was generally large and positive for the constantly rural (R), exurban converted from rural (EfromR), and constantly exurban (E) classes, which were associated with increasing vegetation. The estimated change in annual GPP was high and negative or low and positive for the urban converted from suburban (UfromS), constantly urban (U), and suburban converted from exurban (SfromE) classes, which were characterized by growing built-up areas.

Uncertainties Associated with Land-cover Data

The annual GPP was estimated based on land-cover, solar radiation, NDVI, and LUE. Any uncertainties associated with these datasets and parameters cause uncertainties in the estimates. For instance, the estimated GPP based on the highest LUE values from Turner *et al.* (2003) can reach 3 to 4 times the estimation based on values from Running *et al.* (2000). Despite differences in magnitude of estimates, the overall patterns were found to be stable for annual GPP by development-density categories and its changes by development-direction classes.

The estimation procedure also introduced uncertainties. For example, we used the daily GPP calculated from the maximum NDVI over each 14-day time period as the "daily" estimate of GPP for each day within the time period, whereas actual NDVI changes day by day due to different plant phenology, reflectance of incident radiation, and cloud cover. These variations were not taken into account given the AVHRR NDVI data prepared at a 14-day time step. However, to obtain the daily cloud-free NDVI data is nearly impossible and the 14-day composites are therefore commonly used data in remotely sensed productivity mapping and modeling. For calculation of daily GPP, we used the empirical MODIS NDVI-fPAR look-up table that was developed based on simulated data from the NOAA-11 AVHRR sensor. This might influence the magnitude of our estimated annual GPP in a systematic way throughout the entire study area. For estimation of biophysical parameters, we used constant estimates for the built-up type based on the average fractions of impervious surface, trees, and grass within it. Some variability in these fractions might be expected across the study area, which could be accounted for in future studies by using available estimates of impervious fraction (Yang *et al.*, 2003). Moreover, our estimated GPP did not include contributions from park or wetland land-cover types. Ecosystem dynamics might have changed within these two types. However, since parks are maintained by people, and succession of wetland is a slow progress, we assumed that changes in these two land-cover types may be small during the time span of a decade.

Estimation uncertainties can also come from land-cover data in terms of classification errors (Figure 4). Although the estimated annual GPP continued to be the highest in the exurban development-density category, results of comparison showed that GPP was lower when NLCD (1992) and IFMAP (2000) were used to replace our 1991 and 1999 classifications, respectively, except for the rural type in 1991 and urban type in 1999. We found that higher estimates of GPP for rural areas in 1992 and for urban areas in 2000 may have resulted from lower estimates of built-up by the alternative land-cover datasets. The differences in proportions of built-up between our dataset and that generated from the NLCD dataset (by combining low-density residential, high-density residential, and commercial, industrial or transportation) indicate a more relaxed definition of our built-up type, inclusive of more vegetation. Thus, proportion of built-up by our definition was higher in the suburban, exurban, and rural categories than the proportions derived by the NLCD definition.

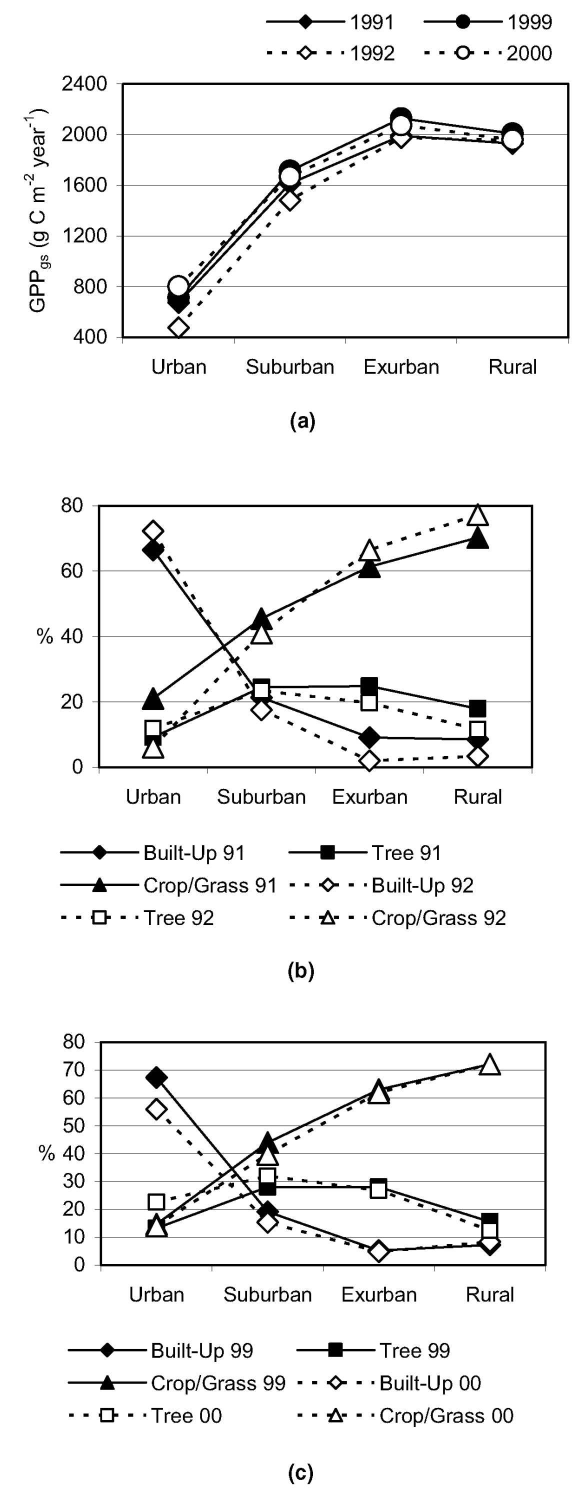

Figure 4. Comparison of results using our land-cover classifications (1991 and 1999) with those using the NLCD (1992) and IFMAP (2000) classifications: (a) estimated annual GPP (GPP_{gs}), (b) land-cover proportions in 1991 and 1992, and (c) land-cover proportions in 1999 and 2000.

Land-cover and GPP Related to Housing-unit Density

In our study, development-density categories based on Census housing-unit density proved to be efficient in capturing land-cover/land-use characteristics along the urban-rural gradient (Figure 4b and 4c). When the maps derived from housing-unit density are associated with the land-cover classifications, urban densities are characterized by majority of built-up, with at least 30 percent impervious surface. Suburban and exurban densities are composed of less than 20 percent built-up and about 20 to 30 percent tree cover, where proportion of built-up is substantially lower in exurban than in suburban. Rural densities are characterized by majority of agricultural crop-land or grassy fields. The estimated GPP and its changes also strongly relate to the four development-density categories and seven development-direction classes (Figure 2). Given the limited correlation between population density and vegetation fraction (Pozzi and Small, 2005), especially in the less densely-populated medium-to-small cities or densely-populated rural areas, the classification of urbanization based on housing-unit density instead of population density enables a stratification tied more closely to human land-use practices. This better facilitates the recognition of heterogeneous changes in land-scape characteristics and ecosystem functions due to human impacts at different levels of intensity.

Conclusions

We analyzed changes in land-cover and gross primary production (GPP) between 1991 and 1999 using remotely sensed data and biophysical parameters for the Detroit-Ann Arbor-Flint Consolidated Metropolitan Statistical Area (CMSA) and vicinity, an urbanizing region of Southeastern Michigan. The pixel-wise changes were aggregated at the scale of the Census block group and then pooled by conversions between development-density categories that are defined from Census housing-unit density.

Despite the continuing urbanization characterized by conversions from lower to higher development densities, we found that the regional annual GPP increased in southeastern Michigan. Increasing GPP was attributed mainly to the increased fraction of tree cover throughout the entire region, including the land maintained as urban and suburban between 1990 and 2000. Additionally, the increase in GPP was strengthened in exurban densities (including those converted from rural land), but was very weak or declining in suburban (including those converted from exurban land) and urban (including those converted from suburban land) densities. We conclude that (a) low-density exurban development increases GPP through the extended vegetation cover; and (b) further intensification of development reduces GPP by subsequent conversion of low-density exurban settlement to high-density urban or suburban settlement.

Human settlement can greatly modify the landscape composition and patterns. Understanding development impacts on carbon dynamics contributes not only to the global estimation of ecosystem production but also to the reliable prediction of future climate. Our measurements of annual GPP and its changes in relation to different levels of urbanization over time provide a basis for the understanding of relationships between productivity and settlement development. Accurate scenarios of carbon budgets may be developed by incorporating localized ecosystem process models into this analysis to evaluate development impacts on NPP and biomass.

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