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Assessing the impact of urban land development on net primary productivity in the southeastern United States

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Abstract

The southeastern United States (SE-US) has undergone one of the highest rates of landscape changes in the country due to changing demographics and land use practices over the last few decades. Increasing evidence indicates that these changes have impacted mesoscale weather patterns, biodiversity and water resources. Since the Southeast has one of the highest rates of land productivity in the nation, it is important to monitor the effects of such changes regularly. Here, we propose a remote sensing based methodology to estimate regional impacts of urban land development on ecosystem structure and function. As an indicator of ecosystem functioning, we chose net primary productivity (NPP), which is now routinely estimated from the MODerate resolution Imaging Spectroradiometer (MODIS) data. We used the MODIS data, a 1992 Landsat-based land cover map and nighttime data derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) for the years 1992/1993 and 2000 to estimate the extent of urban development and its impact on NPP. The analysis based on the nighttime data indicated that in 1992/1993, urban areas amounted to 4.5% of the total land surface of the region. In the year 2000, the nighttime data showed an increase in urban development for the southeastern United States of 1.9%. Estimates derived from the MODIS data indicated that land cover changes due to urban development that took place during the 1992–2000 period reduced annual NPP of the southeastern United States by 0.4%. Despite the uncertainties in sensor fusion and the coarse resolution of the data used in this study, results show that the combination of MODIS products such as NPP with nighttime data could provide rapid assessment of urban land cover changes and their impacts on regional ecosystem resources.
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1. Introduction

Land development in the United States is proceeding rapidly, at a rate faster than population growth (Heimlich & Anderson, 2001; U.S. Department of Housing and Urban Development, 2000; U.S. Environmental Protection Agency, 2000), to accommodate the space demands of an affluent society. From an ecological perspective, land development is one of the most disturbing processes since it dramatically alters the natural energy and material cycles of ecosystems (Berry, 1990; McDonnell et al., 1997; Oke, 1989; Pielke et al., 1999). For example, the carbon cycle is altered due to the subtraction of developed land from the photosynthetic process and the increase in CO_2 emissions from fossil energy use in urban areas. While not all of the land in urban areas is paved, it has been shown that at least in the less resource-limited regions of the United States (eastern and southeastern), urbanization lowers the photosynthetic activity of the landscape (Imhoff, Tucker, Lawrence, & Stutzer, 2000). This observation is particularly relevant when considering that urbanization in the United States occurs preferentially where the soils are most productive (Imhoff, Lawrence, Elvidge, et al., 1997), thereby causing a loss of prime farmland.

In recent years, growth in population size and land occupation has been higher than the national average in the southeastern United States (SE-US) where strong economic forces are reshaping the landscape through urbanization (U.S. Bureau of the Census, 2001). These forces are significantly fragmenting the landscape of this traditionally

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rural region, which also hosts among the most productive forests of the United States (Wear & Greis, 2001). Because of its important ecological resources, the SE-US represents the ideal study area in which to develop a remote sensing based methodology for a regional assessment of the effects of land cover changes, in particular urban land development, on ecosystem resources. Earlier studies on the impact of land cover changes on ecosystem resources have been conducted at either global scales (using coarse resolution data sets) or over small regions (DeFries, Field, Fung, Collatz, & Bounoua, 1999; Houghton, Hackler, & Lawrence, 1999; Imhoff et al., 2000; Paruelo, Burke, & Lauenroth, 2001). A methodology that is consistent across various spatial scales would provide an ideal tool allowing resource managers to map and monitor the impacts of land cover changes.

The recent availability of remote sensing data from the MODerate resolution Imaging Spectroradiometer (MODIS) sensor on-board TERRA (EOS-AM1) platform offers an improved opportunity to monitor ecosystem resources and functioning at regional to global scales. Similarly, improvements to the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) based nighttime data (Elvidge et al., 2001) also allow us to track changes in human settlements. In this study, we explore the combination of the MODIS and DMSP/OLS data sets to assess the impacts of urban development on net primary productivity (NPP) in the SE-US. NPP, the amount of carbon fixed by plants, represents an integrative descriptor of ecosystem functioning and resources because it modulates a number of other ecosystem services ranging from freshwater availability to biodiversity (Field, 2001; McNaughton, Oesterheld, Frank, & Williams, 1989).

Specifically, we address the following issues: (1) What is the extent of recent intensification of urban land development? (2) How has the urban land development impacted regional NPP?

2. Study area

The region examined in this work includes the states of Tennessee, Mississippi, Alabama, North Carolina, South Carolina, Georgia and Florida. These states occupy the southeastern portion of the United States and are characterized by a mild wet climate, with an average annual temperature of 17 °C and annual precipitation greater than 1300 mm. The climate has favored, over time, intense agricultural exploitation, intense timber exploitation and currently, through a strong economic growth, population and urbanization (Alig & Healy, 1987). According to the latest U.S. Census, over 49 million people were living in these seven states in 2000, 20% more than in 1990. It is expected that between 1992 and 2020, urban areas in the South will more than double in extent (Wear & Greis, 2001).

3. Methods

Our methodology used MODIS, DMSP/OLS and Landsat data organized in a geographic information system (GIS). All the data were reproduced at 1 km of spatial resolution and projected to Lambert Azimuthal Equal Area. A high resolution land cover map and nighttime imagery from the DMSP/OLS for the years 1992/1993 and 2000 were used to describe the land cover changes that have taken place in the SE-US as a consequence of recent urban land development. We used NPP from MODIS, estimated using MODIS-derived Leaf Area Index/Fraction of Photosynthetic Active Radiation absorbed by vegetation (LAI/FPAR) and climate data. We estimated NPP contributions from each land cover type in the 1992 land cover map. Using the 1992 land cover as a template, we also identified the surface of each land cover type that has been recently converted into urban use, as inferred from 1992/1993 to 2000 nighttime data change detection. Finally, we estimated the impact of this recent development on the regional NPP as a sum of losses in NPP from each land cover type.

3.1. Mapping southeastern land cover

Predominant land cover types for the SE-US were derived from the 1992 National Land Cover Data set (NLCD) (Vogelmann et al., 2001). This data set was produced at 30 m of spatial resolution from Landsat Thematic Mapper images acquired in the early 1990s and other sources of digital data, mapping 21 land cover classes for the conterminous United States. Overall accuracy for the eastern United States was assessed to be 81% for Anderson level I aggregations (i.e. water, urban, barren land, forest, agricultural land, wetland, rangeland; Anderson, Hardy, Roach, & Witmer, 1976), and 60% for all 21 land cover classes (Vogelmann et al., 2001). The NLCD data set exists both in the native 30-m resolution and in a multilayer 1-km resolution (one layer for each land cover class), in which each pixel reports the percentage land cover type occupied in the square kilometer unit.

We needed a land cover map both to track land cover changes due to recent urban sprawl in the SE-US and to guide the estimation of NPP from MODIS data. Since the MODIS algorithm for the calculation of NPP requires a map of canopy functional types, we grouped the 21 original land cover types from the 1-km resolution product into eight classes, namely, urban, crops, deciduous broadleaf forest, evergreen needleleaf forest, mixed forest (deciduous broadleaf and evergreen needleleaf), grassland, shrubland and barren. We then assigned each square kilometer to the dominant land cover in the pixel (i.e. to the land cover occupying the largest fraction) (Fig. 1). The surface fraction occupied by each land cover on a state by state basis is reported in Table 1.

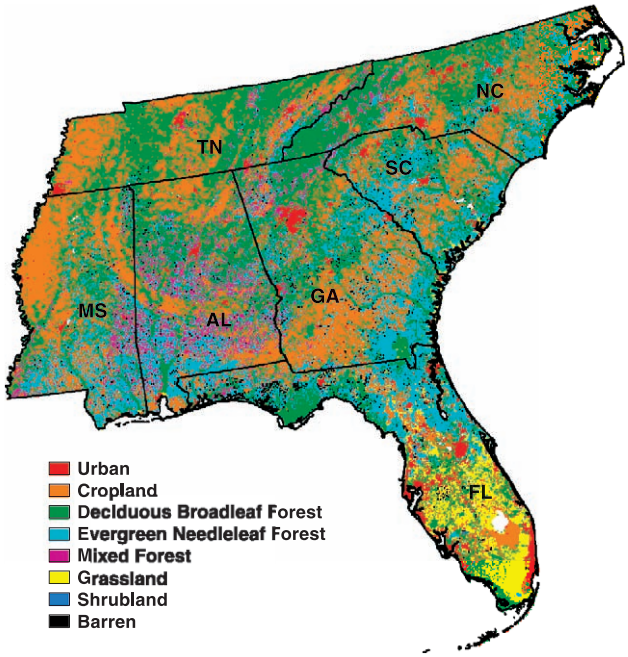

Fig. 1. A 1-km land cover derived from the 1992 NLCD data set (30 m) by assigning each pixel to the dominant land cover within the 1-km unit. The borders of the seven states included in the SE-US region analyzed in this study are imposed on the land cover. AL = Alabama; FL = Florida; GA = Georgia; MS = Mississippi; NC = North Carolina; SC = South Carolina; TN = Tennessee.

3.2. Mapping developed land with nighttime data

Land cover data sets such as the NLCD are useful for several regional and national management applications. However, the large amount of effort involved in their production limits their updating to not more than once every 10 years. While this time scale is more than appropriate for a number of applications, the monitoring of urban growth may require higher frequency assessments in rapidly developing regions. The nighttime imagery from the DMSP/OLS provides the tool for timely and inexpensive monitoring of human settlements (Elvidge et al., 1999; Elvidge, Baugh, Kihn, Kroehl, & Davis, 1997). These data have previously been used to map urbanization in the United States (Imhoff, Lawrence, Elvidge, et al., 1997; Imhoff, Lawrence, Stutzer, & Elvidge, 1997), to estimate population (Sutton, Roberts, Elvidge, & Baugh, 2001; Sutton, Roberts, Elvidge, & Meij, 1997) and to indicate energy consumption and greenhouse gas emissions (Doll, Muller, & Elvidge, 2000; Elvidge, Baugh, Kihns, et al., 1997). At night, the DMSP/OLS sensor operates at high sensitivity in the visible–near infrared portions of the electromagnetic spectrum (0.44–0.94 μm) and is able to detect even faint light emissions from human activity on the Earth. The data are recorded on a 6-bit scale with a nominal spatial resolution of 2.7 km.

In this paper, we used the DMSP/OLS nighttime data to estimate the extent of recent (1992/1993–2000) urban land development in the SE-US. For this purpose, we used average digital number (DN) nighttime lights from cloud-free portions of orbits collected during the dark portions of the lunar cycles during September, October and November of 1992/1993 and 2000. The averaged nighttime lights have a spatial resolution of 1 km. The basic procedure for producing a cloud-free composite for the average DN for lights of each time period (1992/1993 and 2000) can be found in Elvidge, Baugh, Kihn, et al. (1997).

The resulting average DN nighttime lights could not be used directly to estimate the extent of urban land development in the study area since this would produce an overestimate. The use of the raw average DN data tends to overestimate the size of small towns due to several factors, including (1) the large size of the OLS pixel footprint; (2) wide overlap in the footprints of adjacent pixels; (3) accumulation of geolocation errors; and (4) possible inclusion of scattered light due to fog, clouds or haze. We experimentally applied different DN thresholds to the 1992/1993 DMSP/OLS data, below which all the pixels were zeroed. For each threshold, we compared the total lit area to the total urban area by state from the 1-km land cover derived from the 1-km NLCD data, from the original (30 m) NLCD data and from 1990 U.S. Census tabular data. The statistics obtained for a set of thresholds are reported in Table 2.

The total urban area from the NLCD data was derived aggregating the following NLCD classes: low density residential, high density residential, commercial/industrial/transportation and urban/recreational grasses. Then, the percentages of total urban area for each 1-km unit were summed up on a state by state basis. The computation

Table 1
Percent fractions of land cover classes for the seven southeastern states reported from the 1-km land cover

State	Urban (%)	Crops (%)	Deciduous forest (%)	Evergreen forest (%)	Mixed forest (%)	Grassland (%)	Shrubland (%)	Transitional (%)
Alabama	1.8	23.7	35.6	18.8	18.7	0.1	–	1.4
Florida	10.9	13.0	25.8	23.2	1.0	21.6	0.2	3.0
Georgia	3.5	31.2	32.9	25.0	4.4	1.2	–	1.8
Mississippi	1.4	39.3	30.5	21.3	6.1	0.3	–	1.1
N. Carolina	4.9	28.1	47.4	16.1	1.9	0.7	–	0.6
S. Carolina	4.1	27.3	32.2	31.6	0.6	2.3	–	1.5
Tennessee	3.4	35.9	53.5	3.4	3.3	0.1	–	0.3
SE-US	4.4	27.9	36.4	19.8	5.4	4.2	0.02	1.4

Table 2
Comparison of urban area estimates for the seven states of the southeastern U.S. from DMSP data (threshold at digital number (DN) greater or equal to 48, 49, 50, 51 and 52, respectively), from the 1-km land cover, the original NLCD data and from U.S. Bureau of the Census

	DMSP threshold, DN ≥ 48 (km^2)	DMSP threshold, DN ≥ 49 (km^2)	DMSP threshold, DN ≥ 50 (km^2)	DMSP threshold, DN ≥ 51 (km^2)	DMSP threshold, DN ≥ 52 (km^2)	Land cover, 1 km (km^2)	NLCD, 30 m (km^2)	U.S. Census† (km^2)
1992/1993 DMSP data								
Alabama	3967	3821	3688	3522	3379	2353	2274.1	7111.6
Florida	13,491	13,198	12,909	12,617	12,294	15,947	13,086.9	12,318
Georgia	6992	6764	6572	6376	6149	5297	4364.8	5745.2
Mississippi	1837	1755	1664	1584	1484	1696	1770.7	2931
N. Carolina	6362	6127	5893	5634	5448	6254	5756.1	4956.5
S. Carolina	3820	3657	3494	3338	3189	3275	2954.2	2954.2
Tennessee	5051	4870	4697	4524	4346	3656	3709.8	6476.6
SE-US Total	41,520	40,192	38,917	37,595	36,289	38,478	33,916.5	42,493.1
% urban	4.8	4.6	4.5	4.3	4.2	4.4	3.9	4.9
*Threshold DMSP vs. land cover, 1 km**								
$-b$	1.29	1.20	1.32	1.34	1.36			
$-a$	−2042	−1933	−1817.3	−1693	−1588.4			
$-R^2$	0.956	0.9576	0.9577	0.958	0.9595			
*Threshold DMSP vs. NLCD, 30 m**								
$-b$	1.01	1.02	1.04	1.06	1.08			
$-a$	−1121.7	−1034.7	−941.7	−841.6	−759.2			
$-R^2$	0.949	0.9503	0.95	0.9501	0.9512			
*Threshold DMSP vs. U.S. Census**								
$-b$	0.751	0.77	0.78	0.80	0.81			
$-a$	1607.8	1667.5	1727.7	1798.6	1860.9			
$-R^2$	0.7799	0.7829	0.7861	0.7877	0.7885			
t-test, *P*-value DMSP vs. Land Cover, 1 km	0.4554	0.6762	0.9167	0.838	0.6264			
2000 DMSP data								
Alabama	5838	5624	5421	5212	5016			8372.1
Florida	17,263	16,900	16,538	16,185	15,798			15,890.9
Georgia	10,217	9926	9662	9371	9060			7278.6
Mississippi	3242	3099	2963	2818	2679			3872.6
N. Carolina	9601	9269	8933	8629	8291			7306.1
S. Carolina	5853	5637	5417	5202	5004			3390.6
Tennessee	7017	6780	6542	6296	6092			7951.0
SE-US Total	59,030	57,235	55,476	53,713	51,940			54,061.9
% urban	6.9	6.6	6.4	6.2	6.0			6.2
*Threshold DMSP vs. U.S. Census**								
$-b$	0.80	0.81	0.83	0.84	0.86			
$-a$	969	1063.3	1157.4	1264.1	1339.8			
$-R^2$	0.7918	0.7939	0.796	0.7977	0.8011			

* *b* is slope of the linear regression and *a* is the intercept.

† U.S. Census data refer to the year 1990 for the comparison with 1992/1993 DMSP data set and to the year 2000 for the comparison with the 2000 DMSP data set.

indicated that in 1992, the urban areas in the SE-US occupied 33,916.5 m^2 (4% of the total land surface). The total urban area from the 1990 U.S. Census was obtained from tabular data listing the land area of populated places in 1990 on a state by state basis (U.S. Bureau of the Census, 1996). The definition of 'urban' for the 1990 U.S. Census included all the urbanized areas and places with a population of more than 2500. The sum of the land area of all the places with 2500 or more people yielded a total urban area for the region of 42,493.1 km^2 (about 4.9% of the total land surface).

A number of issues challenged our selection of an appropriate threshold for the 1992/1993 DMSP data. One of these issues was the large disagreement (more than 8500 km^2) between the total urban area estimated from the NLCD data and from the 1990 U.S. Census. The 1992 land cover we derived from the NLCD data set, by assigning each 1-km pixel to the dominant land cover in the unit, estimated a total

urban area of 38,478 km^2, a value in between the ones estimated from the original NLCD and from the Census. Since we used this land cover to drive the MODIS algorithms for the estimation of FPAR/LAI and NPP, we decided to use it as the reference layer to compare the total lit area from the DMSP at different thresholds. We estimated the best correspondence by linear regression and with a *t*-test for significant differences. The best correspondence between the total lit area from the 1992/1993 DMSP data and the current land cover was shown for a threshold at a value of DN greater than or equal to 50. While lit area estimates from other thresholds all displayed similar R^2 by linear regression, the estimates from the DMSP with a threshold of DN $\geq$ 50 proved to be the least significantly different from the 1-km land cover estimates of urban area (paired *t*-test, hypothesized difference = 0, alpha = 0.05, *t*-value = 0.1091, *P*-value = 0.9167, $N = 7$). The 1992/1993 total lit area of all the pixel with a DN $\geq$ 50 was 38,917 km^2 (4.5% of the total land surface), and its geographical distribution is shown in Fig. 2a. An alternative to this approach would be the selection of a pair of thresholds, to provide a lower and an upper estimate of the extent of urban area and its impact on NPP.

To determine the extent of total urban area from the 2000 average DN nighttime lights, we applied the same threshold of DN $\geq$ 50, obtaining a total urbanized surface of 55,476 km^2 (6.4% of the total surface) (Fig. 2b). The only data set we had available to verify this value was the total land area of all incorporated urban areas and places with 2500 or more people from the County and City Data Book 2000 (U.S. Bureau of the Census, 2000). According to the U.S. Census data, the total urbanized surface for the SE-US region for the year 2000 is 54,061.9 km^2. While the total estimates are similar for the two methods, wide discrepancies between the state by state estimates exist, especially in the case of Alabama.

A difference image between the nighttime averages of 2000 and 1992/1993 thresholded at DN $\geq$ 50 was used to estimate the distribution of recent land development in the SE-US. While most of the change in nighttime lights over the study area has taken place in the form of an intensification of human activity in areas already developed by 1992, we took into account only those pixels that had no nighttime activity in 1992/1993 and were lit in 2000. The total land developed during 1992/1993–2000 according to our estimate amounted to 16,559 km^2 (1.9% increase) (Fig. 2c).

3.3. Estimation of land cover change effects on primary productivity

One year's worth of MODIS NPP (2001) data are available and distributed by the EROS Data Center Distributed Active Archive Center (EDC DAAC) with the product name of MOD17. However, in this data set, urban areas, along with water bodies, are masked out. As a consequence, we needed to generate our own NPP for the study area. To generate LAI and FPAR (MOD15), the main inputs to the NPP algorithm, we used the MODIS Normalized Difference Vegetation Index (NDVI) (MOD13) and the MOD15 backup algorithm. We downloaded the available MOD13 (NDVI) data for the year 2001 from the EDC DAAC. These data represent 16-day composites of atmospherically corrected maximum NDVI and Enhanced Vegetation Index (EVI) at 1 km of spatial resolution. For a detailed description of the data, see Huete, Justice, and van Leeuwen (1999). In order to cover the study area, three MODIS tiles were required, each covering a ground area of 1200 × 1200 km. We produced a mosaic of the three NDVI tiles for each of the 20 available biweekly composites and reprojected the composites to Lambert Azimuthal Equal Area from the original Integerized Sinusoidal Projection.

The MOD15 backup algorithm uses empirical relations between NDVI and LAI and FPAR derived for various land cover types (Knyazikhin et al., 1999; Myneni, Nemani, & Running, 1997). We used the 1992 land cover map to guide the estimation of LAI/FPAR after rearranging the classes from the perspective of the radiative transfer theory. While urban areas can have substantial amounts of forest vegetation, at the resolution of 1 km^2, most of the urban cover is a mosaic of trees with grass underneath and buildings. As a

Fig. 2. Average nighttime lights with digital numbers greater or equal to 50 for (a) 1992/1993, (b) 2000 and (c) difference between 2000 and 1992/1993. 1 = Atlanta, GA; 2 = Nashville, TN; 3 = Atlanta, GA to Greensboro, NC; 4 = Florida.

consequence, we considered appropriate to assign the urban class to the savanna biome, defined as a two-layer canopy with an overstory of trees and an understory of grasses (Myneni et al., 1997). The land cover class of mixed forest is also not contemplated as an independent structural type from the radiative transfer theory perspective. Thus, we ran the algorithm twice over the pixels classified as mixed forest, once considering them as broadleaf forests and once as needleleaf forests. Assuming that broadleaf and needleleaf species were present in equal proportions in the land cover class of mixed forest, we averaged the LAI/FPAR values of the two runs.

The algorithm used to produce MODIS NPP is shown in Fig. 3 (Running, Nemani, Glassy, & Thornton, 1999; Running, Thornton, Nemani, & Glassy, 2000). The algorithm is based on a light use efficiency logic that relates Absorbed Photosynthetic Active Radiation (APAR) to Gross Primary Productivity (GPP), where APAR = FPAR∗IPAR (IPAR = Incident Photosynthetic Active Radiation). ε_{max} is a biome-specific light use efficiency factor that is modified into ε by daily meteorological conditions (minimum temperature and vapor pressure deficit). ε is used to convert APAR to GPP. NPP is obtained by subtracting maintenance respiration (MR) and growth respiration (GR) components from living tissue material from the annual integral of GPP. LAI is used to compute living biomass, which is a key component of respiration estimation. The meteorological conditions and the IPAR required for the NPP calculation were derived as an average of the 1980–1997 1-km spatially interpolated surface weather observations (Thornton, Running, & White, 1997).

An estimate of total NPP for the 1992 land cover could be obtained in two ways: (1) as a spatially explicit summation of the NPP values derived for each pixel or (2) by multiplying, for each state, the number of pixels in each land cover by its mean NPP. Because of uncertainties related with the land cover accuracy and with the fusion of data from different sources, we applied the second method. Mean NPP for each 1992 land cover class was obtained as an arithmetic average of the total NPP by land cover category in each state, including only those pixels that were not lit in the 2000 average nighttime data with a threshold of DN ≥ 50. We calculated an estimate of NPP also for the barren category, since in the SE-US, this land cover type is

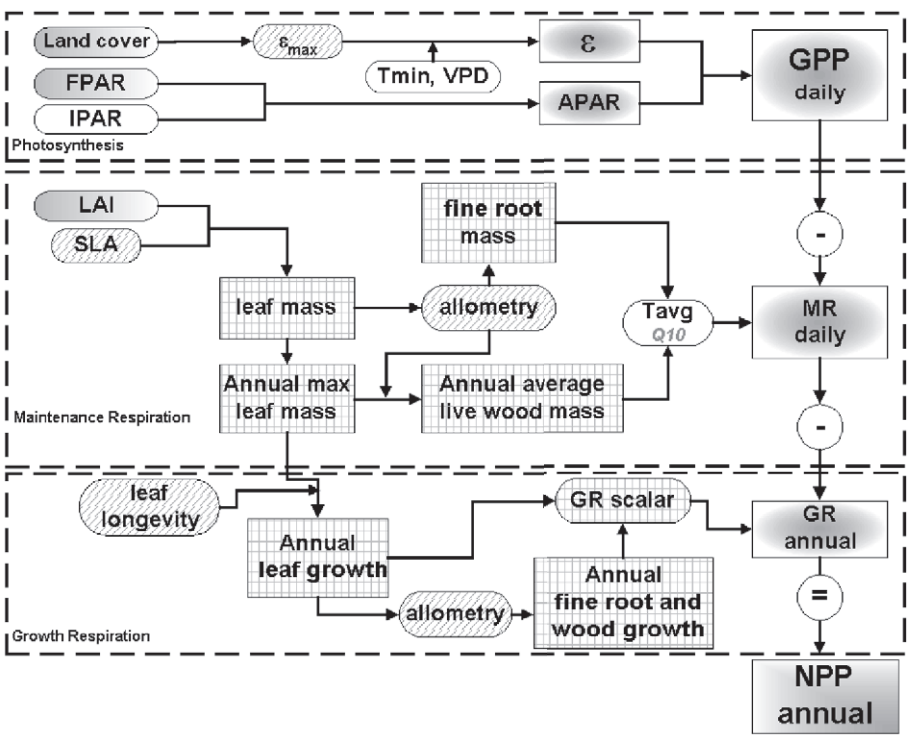

Fig. 3. The MODIS productivity logic has three key components: (1) remote sensing inputs (land cover, FPAR, LAI), (2) daily surface weather (IPAR = Incident Photosynthetic Active Radiation, T_{min} = minimum daily temperature, T_{avg} = daily average temperature estimated from T_{min} and T_{max}, and VPD = Vapor Pressure Deficit), (3) a look-up-table containing biome-specific coefficients (ε_{max}, biometry, leaf longevity and those used in respiration) generated from an ecosystem model. Based on the land cover, a characteristic radiation conversion efficiency parameter (ε_{max}) is extracted from a lookup table. T_{min} and VPD are used to attenuate ε_{max} to produce ε, which is then used with the Absorbed Photosynthetic Active Radiation (APAR) to predict daily Gross Primary Productivity (GPP = ε∗APAR, where APAR = IPAR∗FPAR). Specific Leaf Area (SLA) determined by land cover is used to estimate leaf mass from LAI. Fine root mass is assumed to be in a constant fraction of leaf mass for each land cover. In an annual time step logic, annual leaf mass is assessed from daily leaf mass and used to estimate annual average live wood mass. Maintenance respiration (MR) costs of leaf, fine root and live wood mass are calculated daily as exponential functions of daily average temperature (T_{avg}). Leaf longevity from a lookup table is used to determine annual leaf growth and, through allometric relationships, annual fine root and wood growth and the associated annual growth respiration (GR) costs. Final estimation of annual Net Primary Productivity (NPP) is obtained by subtracting the annual integral of daily MR and annual GR from the annual integral of daily GPP.

represented mainly by a transitional class. The NLCD land cover defines transitional those areas with sparse vegetation (less than 25% of cover) that are dynamically changing from one land cover to another, often because of land use activities (i.e. forest clearcuts, transition between forest and agricultural land, etc.). We assumed that the transitional pixel was previously covered with the second most dominant cover in the 1-km unit. The mean NPP of the transitional pixel was then assigned to be 25% of the mean NPP of the second most dominant cover. For example, if the second largest cover in the pixel was deciduous broadleaf, we assumed the transitional pixel to be a clearcut of this forest type and its mean NPP equals to 25% of the mean NPP of the deciduous forest. While these assumptions might be incorrect, they do not have a large impact on the total NPP because of the small surface occupied by this category.

An estimate of the NPP of the recently developed areas was obtained by multiplying the mean NPP for the urban category of each state by the number of newly developed pixels in the state that were not classified as urban in the 1992 land cover.

4. Results and discussion

4.1. Changes in land cover due to urban sprawl

Fig. 2 shows the 1992/1993 and 2000 average nighttime lights with a threshold of DN ≥ 50 and a difference image between the two periods. The difference image provides an estimate of the most intense land development occurring during the 1990s in the SE-US. It indicates that most of the newly developed land is located at the periphery of the largest urban areas, as already demonstrated in other regions of the United States by Imhoff et al. (2000). Large development is present around Atlanta, GA, from Atlanta, GA, to Greensboro, NC, around Nashville, TN, and in Florida. It cannot be denied that in the recent years, human presence has significantly increased in the SE-US much beyond the urban fringe. A comparison between the raw 1992/1993 and the 2000 nighttime averages indicates a dramatic increase in the presence of lower intensity nighttime lights in the countryside, much higher than the one seen after applying the threshold. While a portion of these low density lights may be attributed to error, we think that most of them are the result of the significant fragmentation process that is taking place in the SE-US landscape. Even if the low-intensity nighttime lights in these rural areas are effectively due to the presence of a built-up structure, we assumed that they would probably occupy a very low fraction of the 1-km pixel, therefore not significantly impacting the regional NPP.

In Table 3, we report the surface in each land cover class that, according to the nighttime lights difference between the 2000 and 1992/1993, showed the most substantial increase in human activity. According to our estimates, between 1992 and 2000, land development has irreversibly transformed about 1.9% of the SE-US. The largest increase in lit surface was recorded for the states of Georgia, Florida, North Carolina and South Carolina. It should be noted that a substantial portion of newly lit areas matches with land already classified as urban in the 1992 land cover. There are a number of factors that could explain this inconsistency; an inappropriate choice of threshold for the DMSP/OLS data would be a significant factor. As listed in Table 2, the total urban area for the SE-US estimated from the DMSP/OLS with a threshold of DN ≥ 50 is similar to the estimate derived from the 1992 land cover, but large differences can occur on a state by state basis. For example, the 1992/1993 DMSP data estimate a urban surface of 12,909 km^2 for the state of Florida, a value 3038 km^2 lower than the figure from the 1992 land cover, which probably is overestimating the real value. The selected threshold for the DMSP/OLS data estimates a smaller urban area than the 1992 land cover also for the states of Mississippi and North Carolina. Another factor contributing to the inconsistency could be related to the preparation of the 1-km land cover from the NLCD data. Assigning the pixels to the dominant cover in the 1-km unit could overestimate the total urban surface if the built-up surface in the pixel was larger than any other cover but less than 50%. Finally, the inconsistency could be due to geolocation errors in the DMSP data or to inaccuracy of the NLCD cover.

Overall, overlaying the nighttime change image with the current biome land cover map indicates that most of the new development (50%) is due to the conversion of forest, in particular deciduous broadleaf forest, which is the dominant

Table 3
Surface area developed between 1992/1993 and 2000 and percent fractions of total land area based on change detection of thresholded DMSP/OLS data for the two composite periods

State	Urban (km^2)	Crops (km^2)	Deciduous forest (km^2)	Evergreen forest (km^2)	Mixed forest (km^2)	Grassland (km^2)	Shrubland (km^2)	Transitional (km^2)	Total (km^2)	Fraction (%)
Alabama	160	552	573	220	216	7	–	5	1773	1.3
Florida	1183	444	809	511	10	650	2	20	3629	2.5
Georgia	348	611	1284	463	346	17	–	21	2739	2.0
Mississippi	209	516	313	210	34	13	–	4	1090	1.1
N. Carolina	621	713	1136	520	32	6	–	12	2419	2.4
S. Carolina	325	542	495	472	2	73	–	14	1597	2.4
Tennessee	233	818	642	49	99	0	–	4	1612	1.7
SE-US	3079	4196	5252	2445	739	766	2	80	16,559	1.9

forest type in the region. About 25% of the new development resulted from the conversion of cropland and almost 5% from the conversion of grassland (mainly in Florida). These statistics are in agreement with the results presented in the Southern Forest Assessment Draft Report (Wear & Greis, 2001). According to the same report, this conversion of forest area into developed land is counterbalanced by a conversion of cropland into forest use. Therefore, it is actually the extent of croplands that is being reduced in the SE-US.

4.2. Effects of land cover change on regional primary productivity

Table 4 reports mean and total NPP estimates for each of the land covers. The 1992 total NPP for the SE-US is estimated to be 872.57 Tg (Teragrams, 10^{12} g) of carbon per year, 68% in forests and grasslands, 28% in crops and about 3% in urban areas. For the urban class, Table 4 shows also the percentage of urban area covered by tree canopies, as measured by Dwyer, Nowak, Noble, and Sisinni (2000). Urban areas retain high primary productivity, which correlates well with the tree cover. The highest urban productivity per unit area is reported for Georgia (848 gC m^{-2} y^{-1}), which also presents the highest urban tree cover in the nation. Another factor contributing to this high productivity is the presence of parks and golf courses, which tend to be intensively managed with irrigation and fertilizers. Golf courses are particularly numerous in this region, which is also one of the prime North American retirees destinations.

Table 5 shows the estimates of NPP loss due to new development as estimated from the change detection analysis of the nighttime imagery. We considered that no loss took place over those areas that appear as newly urbanized from the nighttime lights change detection but were already classified as urban in the 1992 land cover. The average loss in annual NPP per unit area is 183 g of carbon per square meter. The total loss amounts to 3.04 Tg of carbon per year, 0.35% of the total NPP in 1992 and apparently due to about 1.9% increase in the urban surface. This seems a modest loss in NPP and in carbon sequestration potential, probably contained by fertilization and irrigation of the urban vegetation. However, this loss becomes relevant if we consider that it is accompanied by an increase in emissions of CO_2 due to the significant growth in population of the SE-US during the years between 1990 and 2000. This growth, according to the U.S. Census, amounted to almost 8.2 million people, a number equal to the current population of Georgia.

It is also important to understand that changes in land cover due to urban sprawl add to the other changes in land cover that took place in the SE-US, which have left unaltered very little of the original vegetation in the region. Most of the original mixed forest has been replaced by deciduous or evergreen stands for industrial timber produc-

Table 5
Estimates of NPP lost due to estimated development between 1992/1993 and 2000

State	Unit loss in NPP (gC m^{-2} y^{-1})	Total loss in NPP (TgC y^{-1})
Alabama	221	0.38
Florida	153	0.55
Georgia	204	0.63
Mississippi	196	0.26
N. Carolina	178	0.54
S. Carolina	194	0.37
Tennessee	163	0.30
SE-US	183	3.04

Table 4
Estimates of mean and total NPP by current land cover types for the seven southeastern states

State	Urban*	Crops	Deciduous forest	Evergreen forest	Mixed forest	Grassland	Shrubland	Transitional	Total
Mean NPP (gC m^{-2} y^{-1})									
Alabama	800 (48.2)	993	1065	1085	1115	335	–	269	
Florida	749 (18.4)	1066	975	1038	1056	888	844	234	
Georgia	848 (55.3)	1120	1081	1083	1057	712	–	266	
Mississippi	765 (38.6)	958	1023	1077	1117	675	–	263	
N. Carolina	798 (42.9)	1040	1032	997	1068	361	–	241	
S. Carolina	789 (39.8)	1089	1053	1004	1047	585	–	254	
Tennessee	759 (43.9)	905	987	1016	1002	844	–	231	
Total NPP (TgC y^{-1})									
Alabama	1.88	31.51	50.77	27.28	27.89	0.05	–	0.50	139.88
Florida	11.95	20.22	36.69	35.09	1.51	27.98	0.18	1.01	134.63
Georgia	4.49	53.08	54.15	41.14	7.04	1.28	–	0.74	161.92
Mississippi	1.30	46.47	38.44	28.30	8.42	0.22	–	0.35	123.50
N. Carolina	5.00	37.25	62.39	20.40	2.58	0.34	–	0.18	128.14
S. Carolina	2.58	23.80	27.12	25.40	0.53	1.08	–	0.31	80.82
Tennessee	2.78	35.54	57.77	3.82	3.65	0.06	–	0.07	103.69
SE-US	29.98	247.87	327.33	181.41	51.62	31.01	0.18	3.16	872.57

* Between parentheses is the urban tree cover, in percent, reported by Dwyer et al., 2000.

tion and by cropland. Crops, which contribute to almost a third of the primary productivity, are characterized by fast carbon cycling due to annual or biannual harvest. The harvesting of crops is also associated with carbon release from soils. Similarly, the turnover of the carbon from the timber plantation has been accelerated, also reducing the potential for long-term carbon sequestration.

The loss in NPP due to development could be reduced with intensive urban forestry programs, as shown for the state of Georgia, which has been the most successful in maintaining a high urban tree cover. Trees not only sequester more carbon per unit area than grasses, but also contribute to reduce surface runoff and evapotranspiration from irrigated lawns. Other benefits (Nowak & Crane, 2000) include emission reductions from air conditioners (trees provide shade to buildings) and general mitigation of the urban heat island effect. Urban forests also increase opportunities for wildlife survival and reduce land fragmentation.

5. Conclusions

The southeastern states, ecologically important because of their high primary productivity, are undergoing rapid changes in land use and land cover as a result of rapid population growth. In the context of characterizing and quantifying these changes, recent advances in remotely sensed data offer a valuable tool. The integration of advanced products such as NPP from satellite data with a nighttime light map allows not only rapidly monitoring changes in human settlements, but also estimating their impacts on ecosystem resources. Much of the data used in this study is readily available to the public, and should therefore be a valuable resource for communities world-wide.

The results presented in this paper provide a coarse assessment of the extent of urban sprawl and its impact on NPP in the SE-US. The spatial resolution and uncertainties of the input data limit the accuracy of the results. Nevertheless, it provides a methodology for understanding regional effects of urbanization on primary productivity.

Other MODIS products that are routinely produced and may be of use in urban studies include surface albedo, surface temperature and aerosol concentration. Their integration with the LAI/NPP products could provide useful information of the impact of urban areas on energy efficiency and other ecosystem variables. Though not widely available as yet, MODIS also produces 250 m of NDVI data, from which higher resolution NPP could be derived. Once the processing is streamlined, it should vastly enhance the potential for urban studies.

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