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The Effects of Urbanization on Net Primary Productivity in Southeastern China

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Abstract Net primary productivity (NPP) is one of the major ecosystem products on which human societies rely heavily. However, rapid urban sprawl and its associated dense population and economic conditions have generated great pressure on natural resources, food security, and environments. It is valuable to understand how urban expansion and associated demographic and economic conditions affect ecosystem functions. This research conducted a case study in Southeastern China to examine the impacts of urban expansion and demographic and economic conditions on NPP. The data sources used in research include human settlement developed through a combination of MODIS, DMSP-OLS and Landsat ETM+ images, the annual NPP from MODIS, and the population and gross domestic product (GDP) from the 2000 census data. Multiple regression analysis and nonlinear regression analysis were used to examine the relationships of NPP with settlement, population and GDP. This research indicates that settlement, population and GDP have strongly negative correlation with NPP in Southeastern China, but the outcomes were nonlinear when population or GDP reached certain thresholds.

Keywords Human settlement · Population · Gross domestic product · Net primary productivity · Multiple regression analysis · Southeastern China

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Introduction

Urbanization is a process associated with the redistribution of populations from rural to urban settlements; that is, the processes of population increase in urban regions associated with settlement increases. It assumes migration of people to urban areas, an expanding urban footprint on the landscape, and a growing take-out rate of net primary productivity (NPP) to sustain population that no longer depend directly on the productivity of the land. Urbanization exerts substantial effects on carbon exchange between atmosphere and land surface by transforming landscape, changing albedo, and altering hydrological processes (Grimmond and others 2002; Koerner and others 2004). It has been recognized as an important factor in modifying the biological, physical, and chemical characteristics of the land surface, and further affecting the functions of terrestrial ecosystems and climate change (Pickett and others 2001; Goldewijk and Ramnakutty 2004; Zhou and others 2004; Foley and others 2005; Zhang and others 2006; Kaufmann and others 2007; Zhang and others 2008). Therefore, understanding how urban expansion and demographic and economic conditions influence environmental conditions is a prerequisite to better deal with environmental problems. Previous research has indicated the importance of interdisciplinary research on socioeconomic and biophysical factors that affect the carbon cycle (Liu 2001; Alberti and others 2003; Alberti and Marzluff 2004; Redman and others 2004; Ma 2006; Pataki and others 2006; Liu and others 2007).

Human activities are highly dependent on ecosystem goods and services (Costanza and others 1997; Rojstaczer and others 2001), especially NPP (Vitousek and others 1986, 1997; Imhoff and others 2004a, b). NPP—the net carbon gain by vegetation, which equals the difference between photosynthetic gains and plant respiration (losses), is the key process in carbon cycling and the main direct product for human society from ecosystem vegetation (Costanza and others 1997). NPP can be estimated using ecosystem models or from remotely sensed data (Tian and others 1998, 2003; Tian 2002; Zhao and others 2005). For example, NPP has been routinely derived from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) since 2000 (Running and others 2000; Zhao and others 2005). It is estimated that about 31% of the global terrestrial NPP is utilized directly by human society (Vitousek and others 1986; Imhoff and others 2004a). The important role of NPP in carbon cycling and in supplying human demand for food and fiber has made it an active research target in the past several decades (Chapin and others 2002).

One of the major characteristics of an urban ecosystem is its spatial heterogeneity. An urban ecosystem is usually composed of three completely different subcomponents: impervious surfaces (e.g., roads, pavements and buildings), intensively managed urban lawns, and remnants of pre-urbanization ecosystems (e.g., urban forests in many US cities). There are several estimates of the carbon storage of urban forests in the USA (Nowak and Crane 2002; Milesi and others 2003). Urban trees are found to have higher carbon storage (9.25 kg C/m^2 cover) and gross sequestration (0.3 kg C/m^2 cover) on a per unit tree cover basis than the average forest stands due to the relatively open forest structure (Nowak and Crane 2002). Urban vegetation has proven to have higher productivity, however, the land cover changes due to urban development reduced annual NPP of the Southeastern USA by 0.4% per year from 1992 to 2000 (Milesi and others 2003). Imhoff and others (2000) combined remote sensing data with census data to estimate the effect of urbanization on photosynthetic productivity in the USA, and found that annual productivity can be reduced by as much as 20 days in some areas, but in resource limited regions such as arid or desert areas, photosynthetic production can be enhanced by intensive management of urban lawns and trees.

NPP change, as an important indicator of ecosystem functioning, can be used to reflect the environmental problems caused by urbanization (Imhoff and others 2004a, b). Much research focusing on urbanization and the carbon cycle has been conducted in the past (Milesi and others 2003; Imhoff and others 2004b; Zhou and others 2004; Zhang and others 2006; Grimm and others 2008), but the effects of urban expansion, population and economic conditions on the carbon cycle is still poorly understood, except in very broad ways such as the correlation between declining NPP and urbanization. The rapid urbanization of China is causing many environmental problems, such as vegetation loss, air pollution, water shortages and contamination, and urban heat islands. It is essential to examine the impacts of urban expansion, population and gross domestic product (GDP) increases on NPP dynamics, especially in regions like Southeastern China with rapid urbanization.

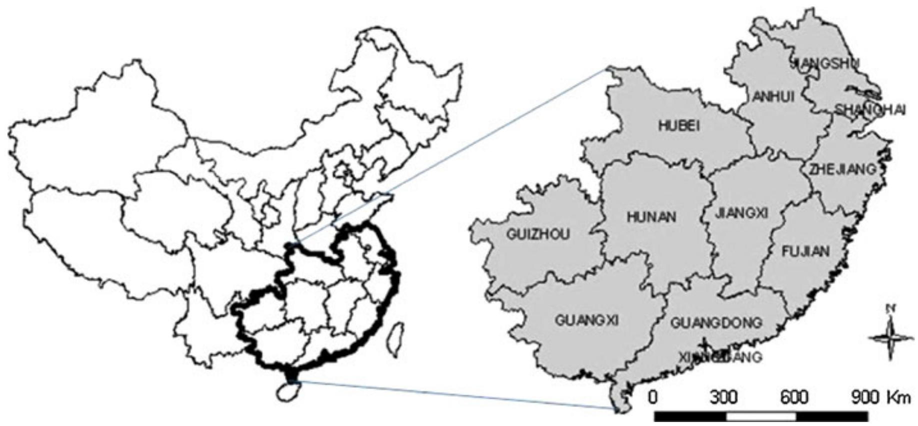
Study Area

China, with the world's largest population (approximately 1.3 billion, accounting for 22% of the world's population), high economic growth rates and rapid urban expansion have generated a great pressure on natural resources, food security, and human welfare (Tan and others 2005, Ostwald and Chen 2006). Population in China increased from 962.6 million in 1978 to 1.14 billion in 1990 and 1.32 billion in 2007. The urban population accounted for 18% of China's population in 1978, 26% in 1990, 36% in 2000 and 45% in 2007 (http://www.stats.gov.cn/tjgb/). The number of cities increased from 69 in 1947 to 223 in 1980 and to 670 in 2006, with 89 cities having population of more than 1 million (Normile 2008). The number of small towns increased from 2,176 in 1978 to 20,312 in 2000 (Zhou and others 2004). With increasing pressure of population and economic conditions, the conversion rate of vegetation and agricultural lands to human settlements has been increasing sharply in recent decades (Liu and others 2005a, b). In particular, Southeastern China has experienced rapid urban expansion along with high population and economic growth rates since early 1980s. This study area covers 10 provinces and one metropolis—Shanghai (Hong Kong and Macao are not included in this research because of lack of data sets) (Fig. 1), and accounts for 15.69% of the total area in China. However, the population and GDP in this region accounts for 44.16 and 54.33% in China according to the China Statistical Yearbook in 2006 (Bureau of Statistics of China 2006). Therefore, Southeastern China is an ideal study area for examining how the changes in urban extent and in demographic and economic conditions affect the sustainability of terrestrial ecosystems.

Methods

Census-based population and GDP data, along with remote sensing-based fractional settlement image and annual NPP

Fig. 1 Study area: Southeastern China by overlaying a boundary layer at provincial level



images were used in this research. The geometric accuracies among these multiple source images were examined and all images had the same spatial resolution of 1 km and were projected to Albers Conical Equal Area. The national population and GDP spatial distribution images were developed from the 2000 census data, which were from the China Natural Resources Scientific Database (www.naturalresources.csdb.cn). A fractional settlement image (proportion of settlement in a cell size of 1 km by 1 km) in the Southeastern China for 2000 was developed with an integrated approach based on a combination of the DMSP-OLS, Terra MODIS and Landsat ETM+ (Enhanced Thematic Mapper Plus) images. Lu and others (2008) have detailed the methods for developing this product and here the fractional settlement image is directly used. The MODIS-derived annual NPP image for 2000 was developed using satellite-derived land-cover, fractional photosynthetically active radiation (FPAR), and leaf area index (LAI) as input surface vegetation information (Running and others 2000), while the necessary climate information was obtained from the Global Modeling and Assimilation Office (GMAO). Detailed description of the algorithm for developing the annual NPP product is provided in the MODIS GPP/NPP Users' Guide (Heinsch and others 2003) and other literature (e.g., Zhao and others 2005; 2006; Heinsch and others 2006). The co-authors (Running and Zhao) provided the annual NPP data for the Southeastern China for use in this research.

The fractional settlement image, population, GDP, and NPP images were stacked into one file. The non-settlement pixels were masked out from the population, GDP, and NPP images based on the fractional settlement image, because this research focused only on the examination of the effects of population, GDP, and settlements on NPP. A window size of 3 by 3 pixels (i.e., 3 km by 3 km in this case study) were selected to extract the mean value of each variable for each sample plot. A total of 125 sample plots were collected and used to examine the NPP relationships with settlements, population and GDP for the study area.

Pearson's correlation analysis is often used to examine the linear relationship between two variables. However, in practice, the relationship between two variables is often affected by other variables; relationships which the Pearson's correlation analysis cannot effectively reveal. In this research, multiple regression analysis and nonlinear analysis are used to examine the relationships of NPP with settlements, population and GDP. NPP is used as dependent variable while settlements, population and GDP are used as the independent variables. In the regression analysis, t test and partial correlation analysis are also conducted.

Results and Discussion

Pearson's correlation analysis shows that NPP has significantly negative correlation with settlement, population and GDP (see Table 1), implying the overall trends of NPP decrease as settlement, or population or GDP increases. Also settlement, population and GDP are strongly correlated each other, implying the uncertainties in evaluating the relative importance of these individual variables in influencing NPP. Since Pearson's correlation coefficient reflects the linear relationship between two variables, it cannot correctly reflect the nonlinear relationships, as the scatter plots show in Fig. 2. Overall, settlement has a strongly linear relationship with NPP, implying that settlement may be an important factor directly related to NPP loss. However, population and GDP appear to have a nonlinear relationship with NPP when population and GDP reach certain thresholds, for example, when population reaches approximately 10,000 person/km^2 and GDP reaches approximately 20,000 RMB (Chinese Yuan) per capita. This situation implies that increase in population or GDP does not mean a continuous decrease in NPP. It is necessary to have a better understanding of their relative roles in affecting NPP.

The multiple regression analysis shows that the coefficient of determination (R^2) is 0.67 and the regression model

Table 1 Correlation coefficients between net primary productivity (NPP), settlement (SET), population (POP) and gross domestic product (GDP) based on Pearson correlation analysis

	NPP	POP	GDP	SET
NPP	1.000	−0.654	−0.578	−0.777
POP	−0.654	1.000	0.605	0.596
GDP	−0.578	0.605	1.000	0.545
SET	−0.777	0.596	0.545	1.000

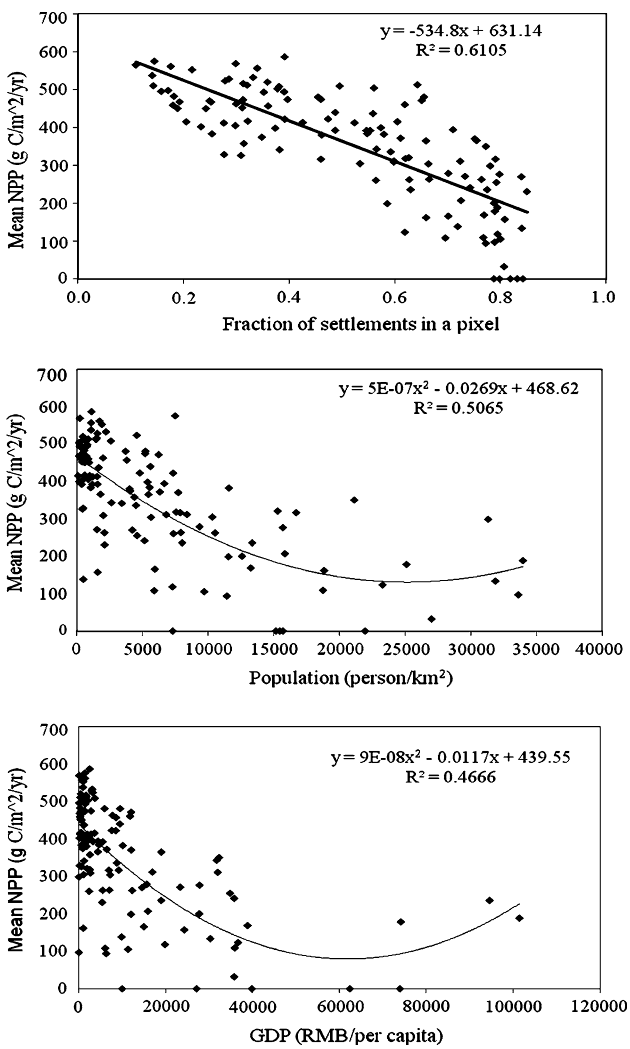


Fig. 2 Relationship between net primary productivity (NPP: g C/m^2/year) and fractional settlement, population, and GDP in the Southeastern China

is statistically significant based on F test. The partial correlation coefficients and the β values indicate that settlement is the strongest factor affecting NPP while GDP is the weakest factor in affecting NPP variation (See Table 2). This finding seems reasonable because settlement increase implies the increase of conversion rates from such land covers as forest and agricultural lands to settlements, thus directly causing vegetation and NPP loss. Population increase is related to settlement increase, but also depends on the building density and heights used per unit of land space. Very high population density may locate in the new residential areas with large and high-rise buildings thereby reducing the spatial area required to accommodate this much larger population. Such residential areas often contain well managed parks that have relatively high NPP. Thus, population is less of a determinant than settlement sprawl in NPP change. GDP is significantly correlated with settlement and population, but GDP is also influenced by other factors such as different industries and use of advanced techniques and management choices. The areas with very high GDP usually have higher investment in green spaces than those areas with lower GDP. For some special situations, higher GDP does not closely accompany a high proportion of settlements, because the regions with very high GDP may be the high-tech companies having plentiful green areas. Therefore, GDP has less importance in influencing NPP than settlement and population.

In reality, the effects of human induced and natural disturbance on terrestrial ecosystems are very complex and interactive. Settlement increase may directly reduce NPP through the conversion of vegetation or agricultural lands to settlement areas or through the generation of air pollution which slows vegetation growth. The same percentage of settlement area on the ground could have significantly different population densities because of different patterns and height of the buildings. Higher population density does not have to reduce NPP because of different land uses and managements applied. The impact of GDP on NPP seems very complex. Higher GDP could increase NPP in some urban landscapes through investments in fast growing trees and increasing green areas (Zhao and others 2007; Buyantuyev and Wu 2009), or modern designs for urban landscapes (Normile 2008). Given that the GDP is rapidly increasing in Southeastern China and may continue to increase for a long period of time, the NPP in Southeastern China might not decline significantly due to urbanization in the future, as shown in other studies (e.g., Grimmond and others 2002; Koerner and others 2004).

The effects of urbanization on NPP could be positive or negative, depending on the local environments (Pouyat and others 2007; Buyantuyev and Wu 2009). The suppression effects of urbanization on NPP might be due to the land conversion from productive natural vegetation to urban land with low productivity (Imhoff and others 2004a, b; Buyantuyev and Wu 2009). The urbanization might also enhance NPP in resource-limited areas. For example, one study conducted in the Phoenix metropolitan region concluded that urbanization may increase regional NPP and increase spatial heterogeneity of NPP in the arid region

Table 2 Results from the multiple regression analysis based on selected samples

Model	Regression coefficient		Standardized regression coefficient	*t*	Sig.	Partial correlation coefficient
	b	SE	*β*			
Constant	596.487	22.221		26.843	0.000	
POP	−0.005	0.001	−0.243	−3.336	0.001	−0.295
GDP	−0.001	0.001	−0.123	−1.767	0.080	−0.161
SET	−389.993	47.727	−0.565	−8.171	0.000	−0.603

$R^2 = 0.67$ based on the multiple regression analysis which NPP is used a dependent variable and POP, GDP and SET are used as independent variables

(Buyantuyev and Wu 2009). Another study in Baltimore concluded that urban trees have higher growth rates than trees growing in non-irrigated and non-fertilized land under rural environmental conditions (Pouyat and others 2007), which is consistent with a number of measurements of the productivity (McPherson 2000; Gregg and others 2003; Hom and others 2003). This study found that the urbanization inhibited NPP over the Southeastern China, which is consistent with the studies in the USA (Imhoff and others 2004a; b); however, it contrasts with a study in Australia where a positive correlation was reported between human population and NPP (Luck 2007). The NPP may increase along with the population density in rainfall-limited areas like Australia because land use management (such as watering the lawn) in urban areas may increase vegetation growth by alleviating resource-limitation (Imhoff and others 2004a). This reverse correlation between NPP and settlement in precipitation-limited and precipitation-abundant areas could also be partially supported by Ramankutty and others (2008), which found that in highly productive biomes, NPP declines with both increased population density and cultivated land area, while in less productive biomes the opposite is observed. Precipitation-limited areas are associated with biomes of low productivity, while precipitation-abundant areas are featured with high productive biomes (Chapin and others 2002). So the suppression effect of urbanization on NPP over the Southeastern China might be due to the weak disturbance from human activity on vegetation and climate coupling and high productive vegetation in rural area.

This study used multiple-source data to examine the impacts of urbanization on the NPP in Southeastern China. When different sources of spatial datasets are used in research, much attention should be paid on the examination of data quality, which often involves geometric accuracies, data formats, projections, and spatial resolutions. In the future, more attention must be paid to uncertainties which may arise when using multiple datasets from different sources. For example, the MODIS-derived NPP data slightly deviate from field observation (Turner and others 2006a, b) and its errors could result from different sources such as land cover classification and climate data. The spatial datasets of GDP and population which were simply extrapolated from county-level census may induce some biases, thus more attention should be paid to more accurately interpolating the census data by incorporating ancillary data such as land use/cover and digital elevation model data. Despite these different uncertainties, this preliminary result in Southeastern China might stimulate more field experiments to verify the relationships between NPP and human settlement, population and economic conditions.

Conclusions

This research shows that settlement, population and GDP have strongly negative correlations with NPP over the Southeastern China. However, the effects of settlement increases and associated demographic and economic conditions on NPP are complex and interactive. Settlement is generally linearly related to NPP, but population and GDP have nonlinear relationships with NPP. This finding questions the simple "more urbanization less NPP", and shows that at certain thresholds increase in population and GDP may induce higher NPP in some urban areas as urbanization disrupts the coupling between vegetation and climate. This finding is cautionary of broad generalizations about these correlations, may stimulate other researchers to examine these correlations in a more nuanced way, and may be useful for policymakers who are managing urban areas and encourage them to consider providing living and recreating green areas for human society.

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