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Urbanization alters spatiotemporal patterns of ecosystem primary production: A case study of the Phoenix metropolitan region, USA

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ABSTRACT

Previous studies have found that urbanization often decreases net primary production (NPP), an important integrative measure of ecosystem functioning. In arid environments, however, urbanization may boost productivity by introducing highly productive plant communities and weakening the coupling of plant growth to naturally occurring cycles of water and nutrients. We tested these ideas by comparing NPP estimated for natural and anthropogenic land covers in the Phoenix metropolitan region of USA using MODIS NDVI data and a simplified parametric NPP model. Most anthropogenic land covers exhibited higher production than the natural desert. Consequently, the combined urban and agricultural areas contributed more to the regional primary production than the natural desert did in normal and dry years, whereas this pattern was reversed in wet years. Primary production of this urban landscape was only weakly correlated with rainfall, but strongly with socio-economic variables. Our productivity estimates agreed well with NPP predicted by a process-based ecosystem model for the area. Significant uncertainties, however, remain due to extremely high heterogeneity of urban vegetation. Nevertheless, our results clearly show that urbanization may not only increase regional NPP and disrupt the coupling between vegetation and precipitation, but also increase spatial heterogeneity of NPP in this arid region.

1. Introduction

Urban development has rapidly transformed landscapes and profoundly altered biodiversity and ecosystem functioning from local to global scales (Grimm et al., 2008; Pataki et al., 2006; Shen et al., 2008). Urbanization is projected to continue to intensify worldwide, and urban sustainability has become one of the most pressing issues that face humanity today (Grimm et al., 2008; Wu, 2008). To develop sustainable urban landscapes, it is critically important to understand the effects of urbanization on ecosystem functioning – an area that has received relatively little research until recently (Wu and David, 2002). This is particularly the case for dryland areas that cover over 40% of the earth's land surface (Warren et al., 1996). Net primary production (NPP), the rate at which plant biomass accumulates in an ecosystem, is a critically important ecosystem process in both natural- and human-dominated landscapes. Aboveground net primary production (ANPP) has been suggested as an integrative measure of ecosystem functioning (Lieth and Whittaker, 1975; McNaughton et al., 1989), and as such it is a key variable in assessing the effects of land use changes on ecosystem conditions.

As the main source of greenhouse gases and other pollutants, cities play an important role in the global carbon cycle (Grimm et al., 2008; Pataki et al., 2006). Fossil fuel combustion and elevated soil CO_2 efflux in irrigated patches of desert cities like Phoenix, USA, produce large amounts of CO_2 (Koerner and Klopatek, 2002). Studies in Phoenix have documented concentrations of near surface CO_2 can be three times higher in the urban core than in the outside desert (Idso et al., 2002). But local and regional carbon sequestration by desert vegetation and soil pools may not be adequate to offset the CO_2 increase, although the potential is still high (Lal, 2004). Wisely irrigated vegetation in urban areas can mitigate the rise in CO_2 by accruing and storing carbon directly via photosynthesis or by decreasing energy consumption via shading and evapotranspiration (McPherson et al., 2005; Nowak and Crane, 2002). Quantification of primary productivity on broad spatial and long time scales, its gains and losses due to urbanization, is critically important to our understanding of regional carbon dynamics.

Traditional means of estimating ANPP by ground measurements are laborious (Sala and Austin, 2000) and prone to uncertainties when scaled up to large areas (Wu et al., 2006). Global and regional estimates of ANPP can be now obtained from remotely sensed data

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coupled with either statistical, or parametric, or process models (Ruimy et al., 1994). Parametric models that utilize Monteith's (1972) original idea of directly relating primary productivity to absorbed solar energy and light use efficiency currently are among the most suitable for use with remotely sensed data (Goward and Dye, 1987; Prince, 1991; Prince and Goward, 1995; Running et al., 2004). These models use relationships found between fraction of photosynthetically active radiation (*fPAR*) absorbed by green tissues and spectral vegetation indexes (SVI) routinely derived by most multispectral remote sensors (Goward and Dye, 1987; Running et al., 2004; Sellers, 1987; Schimel et al., 1991). The product of *fPAR* and incoming photosynthetically active radiation (*PAR*) provides an estimate of absorbed *PAR* (or *APAR*). ANPP is then calculated as the product of the coefficient of energy conversion into biomass (ε) and the annual sum of *APAR*. Recently, Piñeiro et al. (2006) analyzed the performance of the parametric ANPP model in respect to the effects of seasonal dynamics and the number of terms used in the model. They found that if both *PAR* and ε covary with *fPAR* (NDVI) the ANPP can be directly related to NDVI integral, which was also shown by some previous studies (Burke et al., 1991; Prince, 1991; Paruelo et al., 1997; Running and Nemani, 1988; Tucker et al., 1985). Ideally, all three terms should be included in ANPP estimation (Piñeiro et al., 2006). Most primary productivity studies have used 1 km NDVI from the Advanced Very High Resolution Radiometer (AVHRR), but such spatial resolution may not be appropriate for urban studies. Recent data from MODIS (MODerate resolution Imaging Spectroradiometer) instrument aboard the TERRA/AQUA satellites, which have significantly improved spatial and spectral resolutions, offer exceptional opportunities for quantifying urban vegetation and ecosystems processes.

Urban areas are highly fragmented and heterogeneous landscapes shaped by environmental processes and socio-economic drivers. Information on urban vegetation structure and dynamics is not often available making the estimation of primary production difficult. The use of detailed land cover maps that integrate many variables and factors pertinent to primary production is a logical choice in investigating ANPP. Ecologically relevant land cover categories can be associated with dominant vegetation types and used directly to assign parameters of primary productivity models (Milesi et al., 2003; Running et al., 2000). To assess the effects of urbanization on ANPP one can compare relative contributions of major anthropogenic land covers to regional photosynthesis relative to untransformed ecosystems that represent the baseline condition.

Because desert vegetation dynamics is primarily controlled by patterns of water availability (Noy-Meir, 1973; Whitford, 2002) it is expected to correlate highly with rainfall. From the ecosystem functioning perspective, however, rainfall is only a surrogate measure of soil moisture which is determined by hydrological and soil properties (Loik et al., 2004; Schwinning and Sala, 2004). The "inverse texture effect" hypothesis of Noy-Meir (1973) suggests that sandy and rocky soils in desert environments reduce evaporative losses of soil water and limit runoff thus supporting taller and denser perennial vegetation. In contrast to desert, designed urban and agricultural vegetation is maintained to serve a particular socio-economic function and is often expected to show higher levels of primary production.

Our main objective in this research was to quantify effects of urbanization on primary productivity in the Phoenix metropolitan region, Arizona, USA. We utilized the simplified parametric ANPP model that uses *fPAR* estimated from MODIS 250 m NDVI and *PAR* estimated from meteorological data. Detailed land cover information was derived from existing Landsat-based land cover classifications available for the area. Additionally, we investigated annual precipitation and societal factors that are hypothesized to drive ANPP in this arid city. To achieve our goal, we attempted to address the following research questions: 1) Does urbanization lead to an increase or decrease in primary production compared to the native vegetation in the region? 2) What land cover types in the region are the most productive and how does productivity vary among different years? 3) Are there temporal signatures of NDVI that distinguish different land cover classes in this urban region? 4) What is the relationship among rainfall, socio-economic variables, and ANPP?

2. Materials and methods

2.1. Study area

The Phoenix metropolitan region, the home to the Central Arizona–Phoenix Long-Term Ecological Research (CAPLTER) project (Grimm and Redman, 2004), is located in the northern part of the Sonoran Desert, Arizona, USA (Fig. 1). Mean annual rainfall is 180 mm and mean summer temperature is 30.8 °C. Natural vegetation is composed primarily of two subdivisions of the Sonoran Desertscrub – Arizona Upland with paloverde-mixed cacti series (composed of *Cercidium microphyllum*, *Olneya tesota*, *Simmondsia chinensis*, *Larrea tridentata*, *Encelia farinosa*, *Fouquieria splendens*, *Carnegiea gigantea*, and *Opuntia* sp.) and Lower Colorado River with creosote bush–bursage (*Larrea tridentata* and *Ambrosia dumosa*) series (Brown, 1994). Native riparian vegetation is characterized by mesquite (*Prosopis glandulosa*) woodlands and cottonwood-willow (*Populus fremontii*, *Salix* sp., and invasive *Tamarix ramosissima*) deciduous forests (Brown, 1994).

The completion of the Roosevelt Dam on Salt River in 1911 and the selection of Phoenix as the capital of the newly admitted forty-eighth state in the union created a strong impetus for rapid urban growth. Spurred by the development of air conditioning and widespread use of automobiles after World War II, new developments and population increased exponentially, making Phoenix one of the largest U.S. metropolitan areas in 2000 (Gober, 2006). The Phoenix metropolitan area comprises more than twenty municipalities with the total population approaching four million people. It is among the fastest growing urban areas in the United States with urbanization proceeding at the expense of formerly agricultural and desert lands (Grimm and Redman, 2004).

2.2. NDVI data processing

Bi-weekly maximum MODIS NDVI images are automatically generated from surface reflectance data corrected for molecular scattering, ozone absorption and aerosols, and adjusted to nadir and Sun angles with the use of Bidirectional Reflectance Distribution Function (BDRF) models (Huete et al., 1999). NDVI is based on the property of green leaves to strongly absorb red wavelengths (RED) and strongly reflect near-infrared wavelengths (NIR), and is defined as (Huete et al., 1999):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}), \quad (1)$$

where NIR is MODIS band 2 (841–846 nm) and RED is MODIS band 1 (620–670 nm). Maximum bi-weekly compositing of NDVI is the process of combining multiple days of MODIS reflectance and filtering out clouds and data with bad integrity.

We obtained NDVI images (MOD13Q1) for the period 2000–05 and resampled them to UTM Zone 12 coordinates using nearest neighbor interpolation algorithm. All images were checked using quality flags from companion Quality Assurance (QA) images.

2.3. Land cover data

Land cover information was used to aggregate primary productivity estimates and contrast different land covers

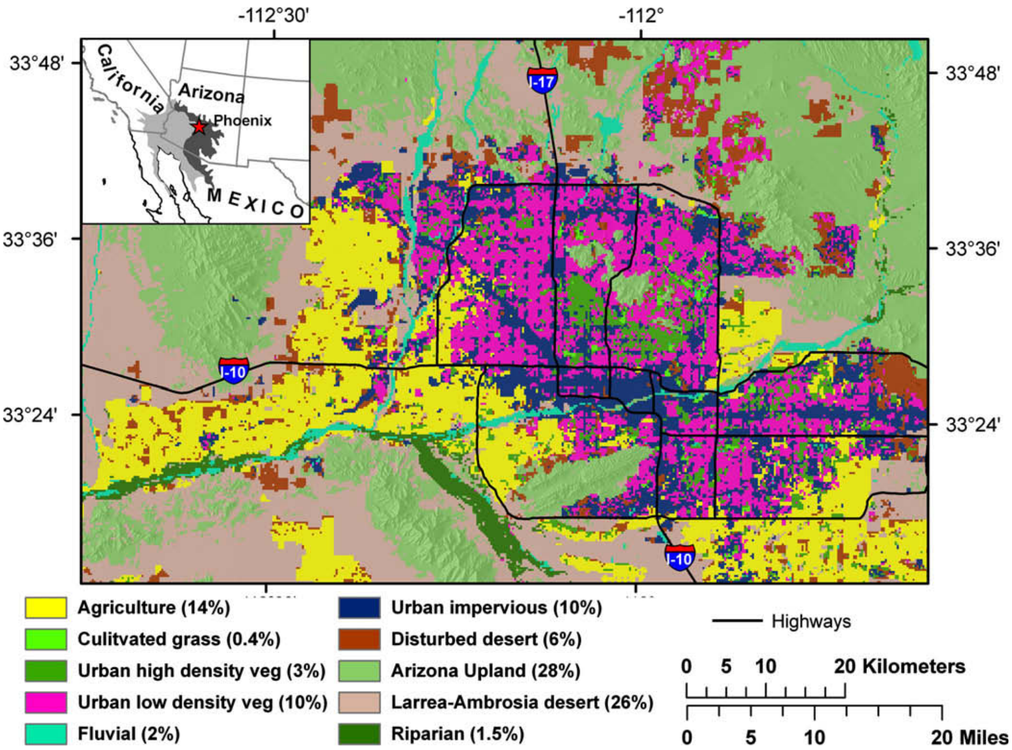

Fig. 1. Study area location and land cover map of the Central Arizona–Phoenix Long-Term Ecological Research (CAPLTER) site. The inset map shows the location of Phoenix where the lighter gray color is the Lower Colorado River subdivision and darker gray is the Arizona Upland subdivision of Sonoran Desert. Class definitions (number in parenthesis is percent of total area occupied by each land cover): 1) agriculture – croplands with agricultural water rights; 2) cultivated grass – actively photosynthesizing vegetation in urban parks and golf courses; 3) urban high-density vegetation – mixture of built materials and dense vegetative cover, predominantly mesic; 4) urban low-density vegetation – mixture of built materials and sparse vegetative cover, predominantly xeric; 5) fluvial – gravels and bare soil associated with water transport features (including canals), standing or flowing water; 6) urban impervious – mixed asphalt, concrete, and building materials with some soil and sparse vegetative cover; 7) disturbed desert – disturbed or bladed soil; 8) Arizona Upland – paloverde-mixed cacti series of Sonoran Desertscrub; 9) *Larrea–Ambrosia* Desert – creosote–white bursage series and saltbush series of Sonoran Desertscrub; 10) riparian – Sonoran riparian woodland and scrubland and riparian Mesquite Bosque with some invasive riparian woodland.

representing the gradient between the urban center and the surrounding desert. We prepared land cover maps by combining two existing Landsat-based classifications – the land use and land cover (LULC) created using Stefanov et al. (2001) model and the provisional Southwest Region GAP (SWReGAP) land cover classification (Lowry et al., 2005). The former was developed as a general LULC reference map for CAPLTER project with the focus on the urbanized area while the latter was created for wildlife habitat and biodiversity modeling. The merger classification was created by using ARC/Info 9.1 software. Urban and agricultural land cover classes were retained from the CAPLTER classification while the undisturbed desert class was replaced by vegetation classes from the SWReGAP map. We also performed class consolidations to eliminate low-accuracy classes from both classifications and make our map more ecologically relevant. The final land cover map depicts two major subdivisions of Sonoran Desert, riparian areas, and ecologically important urban classes (Fig. 1). Landsat images from 2000 to 2005 were used to make two LULC maps and compute land cover changes during this period. This analysis revealed that, although changes took place at the urban fringe, they were not significant to affect our comparison of ANPP patterns along the urban–rural gradient. Consequently the 2000 LULC map was used to stratify all our ANPP analyses.

2.4. Estimation of primary production

We first explored the possibility of using a simple NDVI annual integral to estimate ANPP. NDVI of only two classes, riparian and agriculture, correlated positively with temporal patterns of photosynthetically active radiation (*PAR*). Because NDVI of most land covers did not covary with *PAR* we used the parametric model of primary production of the form

$$\mathrm{ANPP} = \varepsilon\left[\int fPAR \times PAR\right], \tag{2}$$

where ε is the efficiency of energy conversion into biomass, *fPAR* is the fraction of photosynthetically active radiation absorbed by plant tissues, and *PAR* is the fraction of incoming solar radiation in the visible portion of the spectrum (between 400 and 700 nm) in $\mathrm{MJ/m^2} \times \mathrm{h}$ (Monteith, 1972; Running et al., 2000). *PAR* was included as a fixed fraction (0.47) of daily solar radiation measurements (Nouvellon et al., 2000). Growing season in Central Arizona is not truncated by winter frosts, so we calculated primary production on an annual basis. NDVI has been found to accurately quantify *fPAR* (Asrar et al., 1985; Running et al., 2000; Sellers, 1987) and used in the model directly. Since accurate estimation of ε and its seasonal dynamics were not possible for many land covers in the area it was not used in our model. The final model has the form

$$\mathrm{ANPP} = \int NDVI \times PAR \tag{3}$$

Because radiation conversion efficiency (ε) is omitted here, primary production derived from this model is not converted into units of $\mathrm{g/m^2} \times$ year. Piñeiro et al. (2006) found that models without ε can still produce ANPP estimates similar to the full model (±9%), but in areas with high productivity the error can increase up to 19%. Although this can be a potential source of uncertainty in some portions of our study area, i.e. riparian, our estimation can be regarded as the best available proxy of ANPP for the area.

The lack of ground data at the resolution of MODIS sensor did not allow us to directly validate ANPP estimates. However, we were able to verify our estimates for *Larrea–Ambrosia* Desert by comparing with ANPP predicted by a process-based ecosystem model, the patch arid land simulator (PALS), developed for this area (Shen et al., 2005). This physiologically based model simulates dynamics of carbon (C), nitrogen (N), and water cycling of the *L. tridentata* community in Sonoran Desert in a daily time step and with explicit consideration of several plant functional types (Shen et al., 2005). The model was initialized using CAPLTER field data and run for the period of 18 years to allow it to reach a steady-state condition before the evaluation period (2000–05). We compared model-predicted annual ANPP with annual *NDVI* × *PAR* for several years. To minimize spatial uncertainty, time series were constructed for a single pixel in the vicinity of the meteorological station whose data were used to drive the model.

2.5. Analysis of relationships between primary production, annual precipitation, and socio-economic variables

Our preliminary analyses of vegetation phenology suggest that growth cycles in desert ecosystems of the region are highly correlated with temporally lagged accumulated rainfall, so we expected primary productivity patterns to be determined by precipitation. On the contrary, urban and agricultural vegetation dynamics do not respond to temporal and spatial patterns of rainfall. Phenology of designed vegetation appears to be linked to specific ecosystem services, such as crop production, golf playing, or aesthetic. We explored major determinants of primary production in the area by relating spatial patterns of annual precipitation and socio-economic variables with primary production for selected land cover types. Simple bivariate linear correlations between primary production and each of the explanatory variables were computed to evaluate the strength and direction of relationships. Analyses were performed differently for native desert communities and urban vegetation. For desert land cover types, corresponding raster grids of primary production estimates and annual precipitation were overlaid and correlation coefficients computed for all grid cells. To construct precipitation grids we used rainfall data from several national, state, and local weather networks (305 sensors in total). Rainfall point measurements were spatially interpolated using ordinary kriging in ArcGIS 9.1 software. The "inverse texture hypothesis" was tested by stratifying the two desert land covers by soil texture obtained from the Soil Survey Geographic (SSURGO) Database (Soil Survey Staff, 2002).

Socio-economic variables along with annual rainfall were analyzed for two urban vegetation land cover classes – high-density and low-density vegetation. These variables were selected based on previously found relationships for surface temperature, vegetation patterns (Jenerette et al., 2007), and plant diversity and richness (Hope et al., 2003; Martin et al., 2004) in metropolitan Phoenix. Similar to Hope et al. (2003) we extracted three variables (human population density, median household income, and median age of housing structures) from the 2000 decennial U.S. Census for all block groups. Block group is a combination of census blocks, a subdivision of a census tract. It represents the smallest geographic entity for which the desired socio-economic information is available. Block groups were classified into land covers using the majority rule applied to pixels from the land cover map. To make ANPP and precipitation data compatible with socio-economic data we performed scale translation by aggregating them to areas within the boundaries of each block group.

3. Results

3.1. Spatial and temporal patterns of primary production

Our analysis based on maps of *NDVI* × *PAR* shows that ecosystem primary production varied considerably in time and space (Figs. 2 and 3). Among all the land cover types, natural vegetation showed the highest inter-annual variability both spatially and temporally (Fig. 3). For example, primary production increased almost twofold in the wet year (2005) compared to the dry year (2002) in desert scrublands. The most productive were cultivated grasses (golf courses and lawns), agriculture, and riparian ecosystems composed of mesic species (Figs. 1 and 2). Agricultural lands that occupy about 14% of the CAPLTER region exhibited the greatest spatial variation followed by cultivated grasses. Temporal variability of agricultural primary production was also the highest but all other anthropogenic land covers varied the least from year to year (Fig. 3). This could be explained partly by seasonal dynamics of agricultural practices where some areas might remain fallow or otherwise unused for most of the year.

Most of the urban area (about 30% of the CAPLTER region) was characterized by an intermediate level of primary production (Fig. 2). Heavy rains in the winter of 2004–05 caused dramatic increases of primary production in the desert, which minimized the difference between many urban land covers and the outside desert. During dry years, the productivity of cultivated grasses greatly exceeded that of most native desert communities. However this land cover occupied only a small fraction of the entire region, and did not contribute significantly to the regional-scale productivity.

We computed total primary production for combined categories of transformed (agriculture, cultivated grasses, urban high- and low-density vegetation, urban impervious, and disturbed desert) and untransformed (Arizona Upland, *Larrea–Ambrosia* Desert, riparian, and fluvial) ecosystems (Fig. 4). The overall primary production of these categories was calculated within the boundaries of CAPLTER study region where anthropogenic and natural land cover classes occupied approximately equal areas during the study period. When urban and agricultural areas were combined, their total production exceeded that of natural communities in this region during dry (2002) and some normal years (2004). Although the combined desert and riparian vegetation exceeded productivity of urban and agricultural vegetation by 2% in 2001 and 3% in 2003 the difference is insignificant considering that the total area of untransformed land covers was higher by 5% (Fig. 4). Nevertheless, primary production of undisturbed vegetation can be considerably higher than urban and agricultural land covers in wet years such as 2005 (Fig. 4).

Our analysis of NDVI dynamics provides information essential for understanding patterns of annual biomass production in this region. Different land cover types showed distinctive patterns of growth including the number of growing periods, their timing and magnitude (Fig. 5). Unlike urban and agricultural lands, natural vegetation followed predictable seasonal cycles of growth which was mostly driven by the amount and timing of precipitation. The growth in the Sonoran Desert usually starts in late fall and peaks between the end of February and the end of March (Buyantuyev et al., 2007), corresponding to winter–spring rainfall and relatively low air temperatures in springtime. NDVI in urban and agricultural land cover classes was generally higher than in the desert, and had the least inter- and intra-annual variability of growth patterns (Fig. 5).

Comparisons of *NDVI* × *PAR* with PALS-predicted ANPP showed high agreements in terms of both the magnitude and general temporal patterns. The relationship between the two variables is linear with adjusted $R^2 = 0.86$ ($n = 5$, $p = 0.015$). Not only

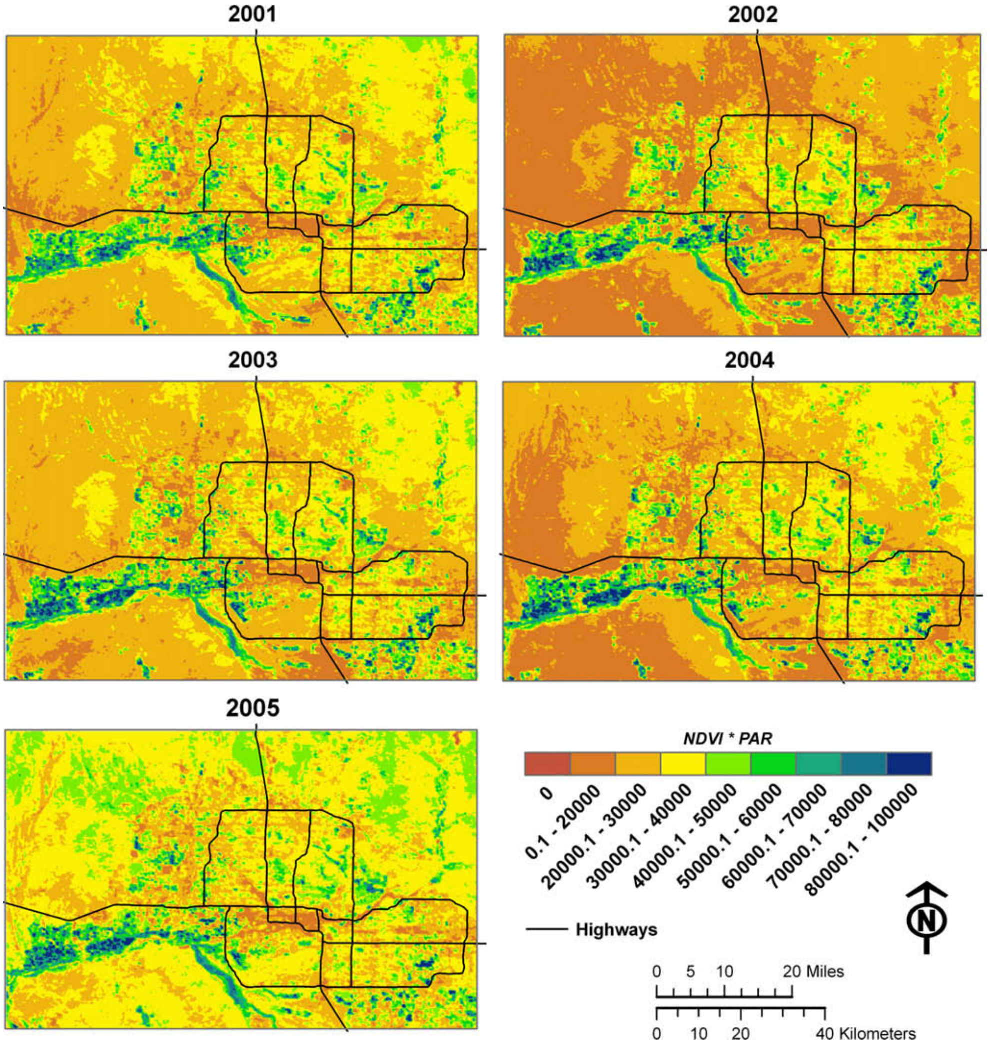

Fig. 2. Annual aboveground net primary production (estimated here as the annual integral of *NDVI* × *PAR*, see text) in CAPLTER at 5 years.

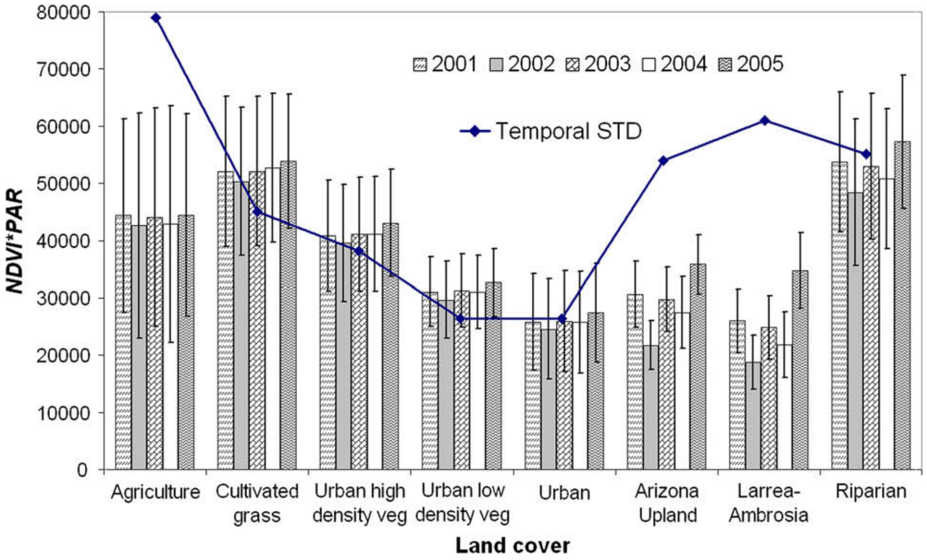

Fig. 3. Mean primary production and its spatial variability (standard deviation) for selected land cover classes at 5 years. Temporal standard deviation is the mean value (by land cover category) of standard deviations computed for primary production estimates at different years.

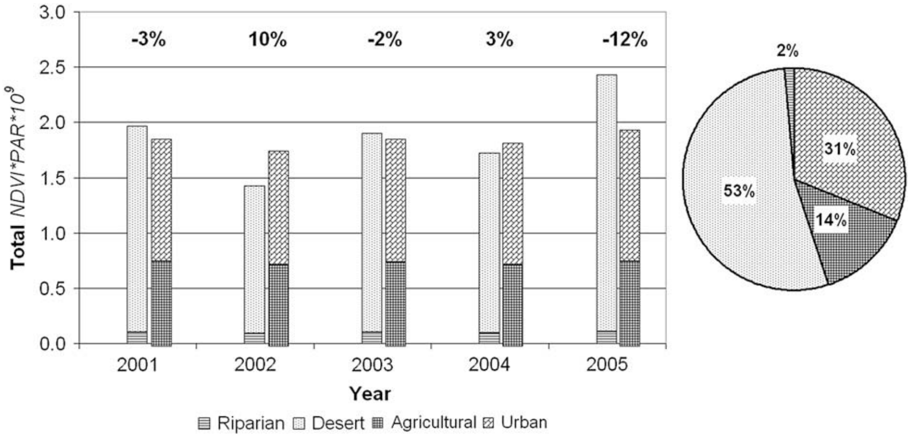

Fig. 4. Total primary production for groups of land cover types (in units of $NDVI \times PAR \times 10^9$) at different years. The pie chart shows percentages of total CAPLTER area occupied by each group. Percent difference above the bars indicates the difference between transformed and untransformed ecosystems where positive number signifies lower production of transformed (urban + agricultural) ecosystems.

productivity estimates agreed but temporal dynamics of NDVI and vegetative cover predicted by PALS co-varied significantly (adjusted $R^2 = 0.54$, $n = 133$, $p < 0.0001$). This indicates the plausibility of using $NDVI \times PAR$ to model ANPP in the area, at least for the *Larrea–Ambrosia* Desert communities.

3.2. *Relationship of primary production to rainfall and socio-economic variables*

The relationships of primary production to annual precipitation and socio-economic variables are shown in Tables 1 and 2. Primary production was better correlated with rainfall in the Arizona Upland regardless of the variations in soil type and annual rainfall. Sandy substrates with high infiltration rates and rapid water percolation seemed to support stronger primary production–rainfall correlations supporting the "inverse texture effect" hypothesis. Vegetation growth on clayey skeletal soils was also highly correlated with rainfall (Table 1). Correlations for all soil types were higher in 2001 and 2004 when annual precipitation was close to the long-term average (normal), but became weaker during very dry or wet years. In contrast, urban vegetation growth was clearly decoupled from precipitation except for primary production of high-density vegetation in 2003 and 2004 and low-density vegetation in 2001 whose correlations were weak and only statistically significant for low-density urban vegetation (Table 2).

Household income was the most important correlate, and the age of housing structures was only weakly correlated with primary production. There are certain differences in time periods when

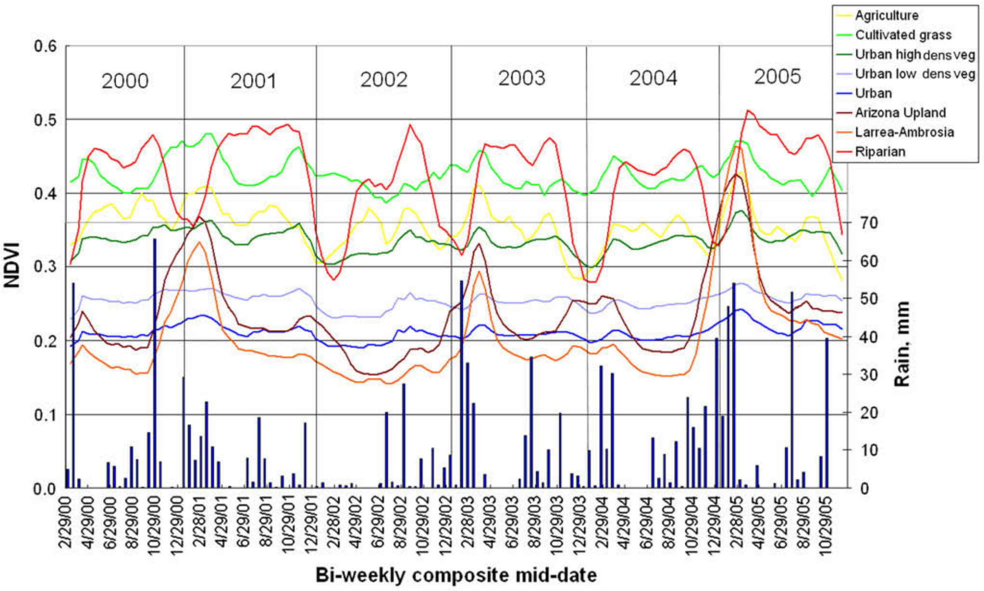

Fig. 5. Temporal plot showing bi-weekly precipitation and spatially averaged bi-weekly maximum NDVI (3-point moving average) for selected land cover types in 2000–05.

Table 1
Pearson product–moment correlation coefficients (r) characterizing relationships between $NDVI \times PAR$ and annual rainfall and computed for different soil texture classes (n = number of MODIS pixels).

Year	Arizona Upland						*Larrea–Ambrosia* Desert			
	Total	Clayey skeletal	Loamy	Coarse loamy	Loamy skeletal	Sandy skeletal	Total	Coarse loamy	Fine loamy	Fine
2001	0.59	0.76	0.63	0.66	0.5	0.82	0.33	0.22	0.24	0.21
2002	0.33	0.44	0.23	0.4	0.34	0.51	0.07	0.1	−0.04*	−0.23
2003	0.31	0.25	−0.18	0.22	0.2	0.19	0.22	0.19	0.23	0.04*
2004	0.67	0.74	0.53	0.62	0.54	0.66	0.29	0.15	0.13	0.36
2005	0.48	0.33	0.36	0.54	0.38	0.55	0.26	0.18	0.2	0.17
n	33,877	6568	1587	1367	11,807	510	31,896	9798	7434	2803

*Correlation is not significant at $\alpha = 0.05$.

contrasting yard landscaping motifs were prevalent. The majority of higher density vegetation neighborhoods were developed in the period between the 1960s and 1980s, whereas low-density vegetation ones were built up mostly in the 1980s and 1990s. Finally, primary production was strongly negatively correlated with human population density (Table 2).

4. Discussion and conclusions

Our results showed several major trends in the dynamics of primary production in response to urbanization in the Phoenix metropolitan region (Figs. 2 and 5). First, conversions of natural vegetation to agricultural and urban land covers can result in both an increase (agriculture, cultivated grasses, high-density urban vegetation) and a decrease (commercial and industrial areas and transportation networks) in primary production. The overall effect depends on the relative proportions of these land cover classes. Our findings of the overall effects of urbanization on primary production in Phoenix are in contrast to those reported for forested areas (Imhoff et al., 2004; Milesi et al., 2003), and suggest that urbanization can substantially increase regional primary production in an arid environment. Our results generally agree with those of Imhoff et al. (2004) who found that urban areas in the southwestern region of the United States as a whole are characterized by a gain in ANPP of 25 g C m^{-2} over non-urbanized areas. We argue, however, that such gains/losses in primary production need to be evaluated at finer scales for improved accuracy, and that the composition of the urban landscape must be considered explicitly to facilitate the understanding of causes and mechanisms of these changes.

Second, because the gain in primary production in the urbanized landscape is not evident during wet years, temporal variability must be quantified for long-term assessment. We found that differences in total primary production between anthropogenic and natural areas were also affected by inter-annual variations of different land cover types. In particular, urban low-density vegetation (mostly residential yards with xeric landscaping) consisting typically of desert plants that received water throughout a year was more productive than similar natural desert plant communities in normal and dry years. The production of the *Larrea–Ambrosia* dominated desert nearly doubled in wet years while low-density urban vegetation stayed at the same level (Fig. 3). The two land covers were different in that urban vegetation had generally lower density due to the presence of impervious surfaces (pavements and buildings) which are essential elements of any urban landscape. Perennial herbaceous plants and ephemerals (annual forbs and grasses) are abundant in the presence of sufficient soil water in the outside desert (Beatley, 1974; Patten, 1978) but they are generally in lower abundance in cities. The 200-point survey conducted in 2005 by CAPLTER recorded much higher richness of annuals species in desert sites (19 species, st. dev. = 7.2, $n = 70$) compared to 8 species in urban (st. dev. = 5.1, $n = 111$) and 8 in agricultural (st. dev. = 4.2, $n = 16$) sites. Significant proportion of urban soils in Phoenix is the result of conversion from agriculture where soil seed banks are potentially depleted due to agricultural practices. Forbs and grasses are essential to desert productivity and can contribute up to 15–18% of Sonoran Desert ecosystem level ANPP (Chew and Chew, 1965; Shen et al., 2005). Overall, in normal and dry years, the total primary production was higher for anthropogenic than for natural land covers, but this pattern could be reversed in wet years. Thus, desert ecosystems determine inter-annual dynamics of ANPP. Yet, desert riparian areas remain the most productive ecosystem regardless of precipitation dynamics. Occupying only 1.5% of the total area, they are exceedingly important in maintaining many ecosystem functions in this area. Preservation and restoration of riparian corridors inside and outside of the urban landscape should be of high priority.

Table 2
Correlations between primary production estimates, rainfall, and socio-economic variables for two urban vegetation classes computed at the scale of census block groups (number of block groups is in parentheses). Values in the table are Pearson's product–moment correlation coefficients (r) between $NDVI \times PAR$ and each of the variables listed in column headings: PRECIP – annual precipitation (mm), POP – population density (persons/km^2), INCOME – median household income (US$/year), BUILT – median age of housing structures (year built).

Year	Urban high-density vegetation (194)				Urban low-density vegetation (995)			
	PRECIP	POP	INCOME	BUILT	PRECIP	POP	INCOME	BUILT
2001	−0.03*	−0.4	0.53	−0.17*	0.18	−0.21	0.26	−0.08*
2002	0.08*	−0.36	0.52	−0.21*	−0.01*	−0.14	0.19	−0.16
2003	0.23*	−0.4	0.53	−0.17*	−0.04*	−0.21	0.25	−0.08*
2004	0.22*	−0.4	0.56	−0.16*	0.04*	−0.23	0.29	−0.07*
2005	0.02*	−0.41	0.55	−0.17*	0.04*	−0.27	0.3	−0.07*

*Correlation is not significant at $\alpha = 0.05$.

Third, human supply of resources, primarily water and nutrients, has effectively decoupled the vegetation growth of urban and agricultural land cover types from precipitation. As a result, the temporal pattern of primary production of cultivated vegetation was weakly or even negatively correlated with precipitation pattern. Our results further extended the concept of the so-called "luxury effect" – plant diversity increased with higher household income levels in the Phoenix metropolitan region (Hope et al., 2003; Martin et al., 2004) – from a biodiversity to ecosystem functioning perspective. Jenerette et al. (2007) also showed that more affluent neighborhoods were characterized by lower air temperatures. In addition, human population density was strongly negatively correlated with ANPP. These results together have important implications for urban planning and management. Quantification of spatial distributions of environmental amenities related to biodiversity and ANPP is important for formulating policies relevant to environmental justice (Environmental Protection Agency, 2003).

Fourth, residential land uses constituted a significant portion of the urban landscape and contributed the most to the regional-scale ANPP. Historically, mesic landscaping, which corresponds most closely to our high-density urban vegetation land cover class, was common for residential yards in Phoenix. With the advent of air conditioning in the 1960s and recent municipal policies for water conservation, large shade trees and grassy lawns have been increasingly replaced with xeric motifs (Martin et al., 2003). Our remotely sensed data analysis confirms Martin et al.'s (2003) finding that desert-like and an oasis (a combination of mesic and xeric) landscaping types predominated in new developments, mostly planned communities with governing boards or homeowner associations. These areas correspond to our low-density urban vegetation class and occupy more than 10% of total study area compared to only 3% occupied by high-density urban vegetation. Considering that productivity of xeriscapes is much lower than that of mesic residential yards, the current trend of increasing the extent of xeric landscaping implies a decrease in future ANPP of the urban landscape. This decrease will be amplified in view of the expected reduction in agricultural land at the expense of new residential developments (Berling-Wolff and Wu, 2004).

MODIS NDVI data have great potential for urban ecological studies. A major source of error is the spatial resolution of the sensor which makes it highly susceptible to the problem of mixed pixels common in studies of urban environments (Mesev, 2003). Another challenge is the sparse desert vegetation responsible for increased soil reflectance and high variability of soil background (Okin and Roberts, 2004; Tueller, 1987). Our study utilized detailed land cover information derived from Landsat imagery and then translated it to the scale of MODIS data. This allowed us to minimize spatial uncertainties. However, uncertainties due to high temporal variability of desert vegetation and limitations of the standard NDVI product still existed in our study as vegetation dynamics below the time span of 14–16 days were undetectable. This problem can be partially alleviated by obtaining raw surface reflectance data and computing NDVI at a time step of 1–2 days. Cloud-free conditions frequent in the Sonoran Desert and other arid regions should make this option feasible. Further work is needed for calibrating MODIS NDVI data and developing landscape-scale process models for estimating ANPP in this urbanizing region. This study is an important step toward these future goals.

In conclusion, our results show that, in normal and dry years, most anthropogenic land covers have higher productivity than natural desert vegetation in the Phoenix metropolitan region. During wet years, however, primary production of the managed land cover types (urban and agriculture) did not change much because it was essentially decoupled from precipitation. In contrast, desert ecosystem primary production increased significantly and was a more major contributor to regional productivity. This finding has important implications for predicting long-term environmental impacts in the face of accelerating urbanization and future climate changes (Grimm et al., 2008; Shen et al., 2008). As most climate models predict a warmer and drier climate for this area (Ellis et al., 2008), the difference in primary production between the metropolitan region and the native desert may become larger. While some have predicted that western United States will remain a carbon sink in the foreseeable future (Bachelet et al., 2004), the effects of rapid and extensive urbanization in this region seem to have a potential to significantly alter the carbon source–sink relationship.

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