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Vegetation productivity trends in response to urban dynamics

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ABSTRACT

Urbanization is a global phenomenon with still unknown consequences for vegetation dynamics of urban ecosystems, especially in subtropical areas of developing countries. In this paper we analyze the vegetation productivity trend associated to urban densification and urban expansion during the last decade, in twelve cities of northern Argentina. We used time series analysis of MODIS-NDVI images to reconstruct the phenological patterns to retrieve a productivity trend under three spatial classes of urban dynamics: (1) urban, (2) expansion and (3) periphery. Our results show that trends in vegetation productivity are more associated to the environmental characteristics (basal productivity and climate) than to the land cover class. The average trend in productivity in urban areas ranged between −2.54% year^{-1} (Metán) and −0.22% year^{-1} (Concepción). In contrast, the range was much tighter between classes; it was −1.37% year^{-1} in urban areas and −1.21% in the periphery. In this sense we found significant differences between cities, but no significant differences were observed between classes. Urban growth and urban expansion patterns found in our study suggest the system dynamics is dominated by sprawl patterns rather than by a homogeneous densification. Related to this phenomenon, our results dismissed the idea of urban expansion as the main factor affecting vegetation phenology and supported the hypothesis of regional warming as an explanation for the decrease in vegetation productivity, probably due to the decrease of water balance in arid regions.

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1. Introduction

Urbanization, (the increase of the share of population living in urban areas) is a global phenomenon with a rapid and deep impact on land cover and land use dynamics. Urban densification (the increase of the share of built area within a city) and urban expansion (the increase of built area occupied by a city) are two spatial processes related to the demographic process of urbanization (Satterthwaite et al., 2010). These spatial processes are the most persistent and extreme anthropogenic land transformations (Palomino and Carrascal, 2006; Shochat et al., 2006; Mckinney, 2006) that transforms, not only the portion of land directly engaged but the ecological processes at local and regional scale. Several authors consider land use/cover change as the single most relevant variable of global environmental change affecting ecological systems (Vitousek, 1994; Vitousek, 1997; Sala, 2000), with an impact on the environment that is at least as great as that associated with climate change (Skole et al., 1994). With most of human population currently living in cities, urbanization and urban expansion are still accelerating processes with unknown consequences for the future of ecosystem functioning. Recent estimations show that 75% of human population will live in cities by 2050, with most of the urban growth occurring in middle size cities of developing countries (United Nations Report, 2014). From a global perspective, the consequent urban expansion could represent a turning point in the life of the planet (Alberti, 2015).

Although urban areas cover less than 5% of Earth's land surface, they are responsible for most of the greenhouse gas emissions, energy use and waste production at global scale (Glaeser, 2011). The expansion of cities transforms natural and agricultural lands into built-up areas (Marzluff and Ewing, 2001), with direct effects on matter and energy fluxes which, in turn, alter ecosystem functions. Urban expansion and densification could affect vegetation functioning, altering the photosynthetic activity and hence primary productivity (Alberti, 2015; Matthews et al., 2011) through direct (elimination of vegetation) and indirect effects (impervious surfaces modify water balance and heat exchange, Paolini, 2012; Gioia et al., 2014). Thus, urban expansion and densification could induce phenotypic responses, which could alter the rates of primary production and carbon sequestration in terrestrial ecosystems (Alberti, 2015). For example, in temperate areas urban heat

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island could extend the growing season of vegetation, but in arid areas it could exacerbate droughts and reduce the growing season (Shochat et al., 2006). In tropical and subtropical regions the effects of urban dynamics on vegetation phenology is unknown, and these effects could be determined to some extent by local or regional environmental characteristics.

One of the main characteristics of urban expansion is that it is not a “one time” event but a continuous process in which land cover change and vegetation dynamics interact through space. Globally, urban expansion and ecological processes are closely related to the spatial configuration of the landscape (Alberti et al., 2008; Wu, 2014). Spatial patterns affect the structure and functioning of urban vegetation, but it is unclear how different spatial patterns of land use and land cover affect ecological processes associated with urban vegetation (Alberti et al., 2008). Net primary production (NPP) mediates the relationship between anthropogenic land cover change and ecosystem functioning (e.g. richness of both fauna and flora species), but this relationship varies with taxa and scale, and across biomes (Mittelbach et al., 2001). In this context, vegetation productivity is a good proxy for an important set of relevant ecosystem services (e.g. water supply, productivity of soils, biodiversity, etc.), with a great impact on human wellbeing.

Trend analysis of vegetation functioning is central to understand the environmental dynamics associated to global change, and requires new and improved tools to assess dynamic processes associated to spatial patterns in a cost effective manner. For many purposes, remote sensing provides the only means to assess habitat structure, land cover changes and environmental dynamics across broad areas (Foody et al., 2003; Kerr and Ostrovsky, 2003; Turner et al., 2003). A wide variety of methods have been developed to study land cover change and its impact on vegetation dynamics (e.g. Paolini et al., 2006; Kerr and Ostrovsky, 2003; Turner et al., 2003; Coppin et al., 2002), being the most popular the post-classification comparison method (Foody, 2002). Most of these approaches rely on the comparison of one or few images per year, reflecting states of vegetation, from which functioning parameters are inferred. For example, maximum NDVI in a set of images is usually used as a measure of yearly vegetation production. The results of this approach are highly dependent on the specific dates of the data, they do not take into account inter-annual fluctuations of vegetation activity and they cannot quantify the cumulative photosynthetic activity as an integrated measure. These are key limitation to reconstruct and assess ecosystem dynamics, that can be overcome using information of all the available images in a particular dataset.

In this paper we assess the impact of urban expansion and densification on local vegetation productivity trends. We analyze this patterns in the past decade in rapid growth cities of subtropical South America, through the use of satellite data with high temporal resolution. Detection, evaluation, and prediction of changes in natural environments are among the most important tasks in landscape ecology studies. The analysis of intra and inter-annual vegetation phenological patterns is a key tool to understand how ecosystems respond to land use and land cover change over time. Vegetation functioning is linked to several processes such as carbon fluxes, hydrology and energy budgets in urban areas. Understanding the mechanisms by which species respond to human-built environments is critical to predict future evolutionary trajectories and adaptation in an urbanizing planet.

2. Materials and methods

2.1. Study area

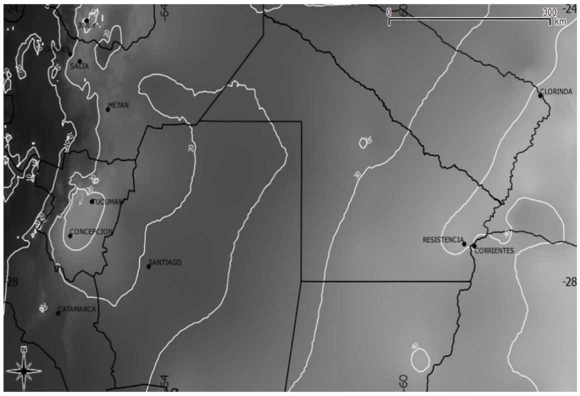

Fig. 1. Urban areas analyzed in Northern Argentina (black dots) and Martonneís aridity index isolines – in white – (values >60 indicates excessively humid areas, and values <10 corresponds to dry or arid places).

To assess the effect of urban dynamics on vegetation productivity during the last decade we analyzed the twelve main urban ecosystems of northern Argentina, representative of middle size, rapid growing cities in developing countries (Fig. 1). The study area spans east-to-west from the wet Chaco region (800 mm of annual precipitation) to the dry Chaco (400–600 mm of annual precipitation) and to the Yungas region (1000–1500 mm of annual precipitation). The climate is subtropical with dry season (dry winters, rainy summers). The rainy season extends from November to March in the Yungas (with more than 80% of the rain occurring during this period). Rainfall regime is less stationary to the east, at the eastern border of the humid Chaco region. Local combinations of rainfall and temperature generate different water balances, which can affect vegetation productivity and phenological patterns.

2.2. Data collection

To characterize the urban dynamics of each city, we classified Google Earth images at the beginning and at the end of 2000’s decade. Satellite images of Google Earth are not available for every date, so we considered some constraints to choose the dates. Images had to be separated by at least eight years and the first image should have been acquired near year 2000. For every urban area and for the two dates we made a visual classification to identify two cover types: urban areas and non-urban. Population data for 2001 and 2010 were collected from Argentinean statistics bureau (INDEC).

Differences in local climate patterns were used to assess the effect of urban dynamics on the vegetation productivity of the cities. We use De Martonne aridity index (Martonne, 1926) as an indicator of the water balance at a given location (relation between yearly mean precipitation and yearly mean temperature). Despite the name of the index higher figures indicate a better water balance.

We used 16-day composites (MOD13Q1) Normalized Difference Vegetation Index (NDVI) estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) images from 2000 to 2012 to describe temporal patterns of vegetation phenology. For every year, vegetation phenology was estimated from 23 composite images of NDVI with values rescaled from 0 to 1, with a spatial resolution of 250 × 250 m. A compound time series of 299 NDVI images was analyzed using TIMESAT software (Jönsson and Eklundh, 2004). TIMESAT quantifies phenological signals from time series of satellite data, adjusts local functions for each point and combines these functions in a model of phenological patterns. Based on these functions, TIMESAT provides statistical descriptors of the seasonal pattern of the analyzed variable (NDVI in this case) through the year. For this study, we used the seasonal total integral (STI), the phenological variable that best summarizes the annual dynamics of the Growing Season (GS) of the vegetation. The STI is an indicator of absorbed photosynthetically active energy accumulated in one

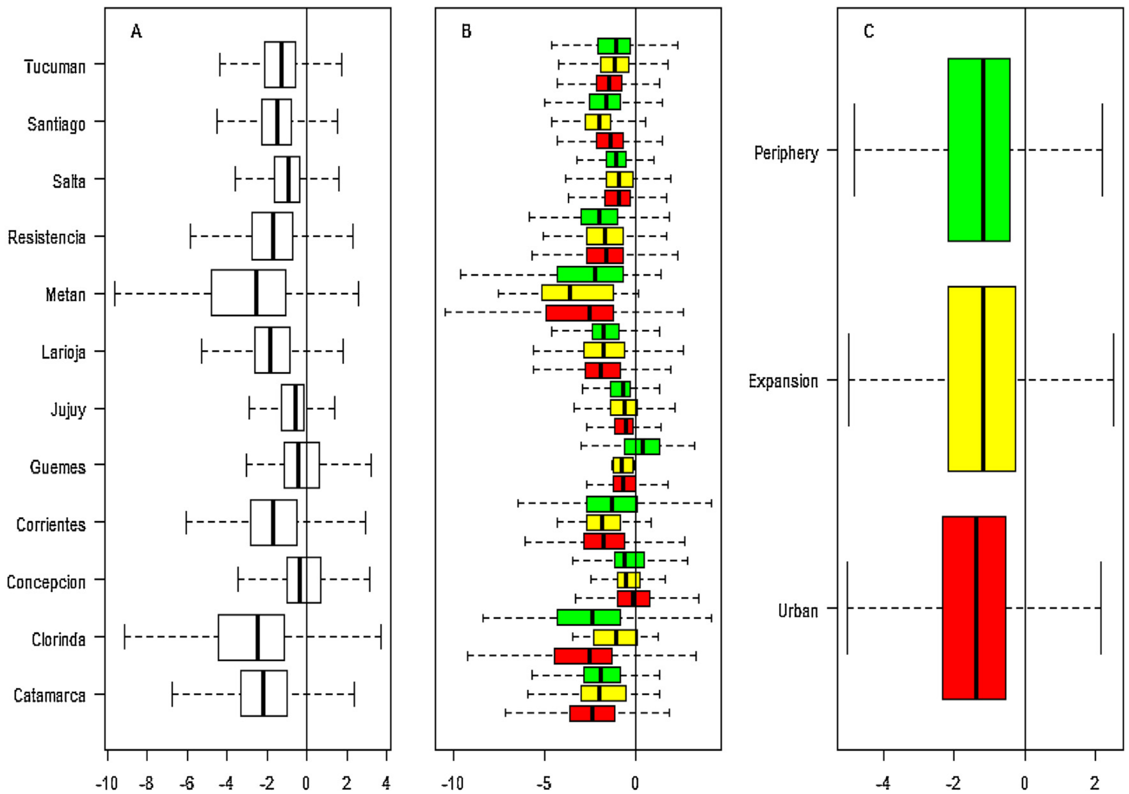

Fig. 2. Mean percent Sen slope in vegetation productivity from 2000 to 2012. Pixel data are clumped by (A) cities; (B) cities and land cover classes and (C) land cover classes.

GS (Running et al., 2004), so it can be used as a proxy of gross primary productivity. Since the study was carried out in the southern hemisphere, GS and calendar year are dephased.

2.3. Data analysis

For every pixel in our study area we estimated the time trend of STI from 2000 to 2012 using the non-parametric Theil Sen estimator (Theil, 1992; Sen, 1968). This estimate, also known as Sen Slope, is the median slope of every pair of points in the time series, which makes it robust since it is not sensitive to potential outliers. Moreover, it does not make assumptions about the distribution of sampled data (Logan, 2010). We transformed the slope to percentage of the average productivity of the twelve years because STI has no dimensions or units so it cannot be easily analyzed and because the raw value of the trends could be affected by the amount of productivity which is associated to environmental conditions.

Every pixel was assigned to a city and to one of three land cover classes: (1) urban (areas classified as urban at the beginning and at the end of the analysis); (2) expansion (areas classified as non-urban at the beginning and as urban at the end of the analysis) and (3) periphery (areas adjacent to the cities that were labeled as non-urban at the beginning and at the end of the analysis). Pixels were clumped depending on the city, classes and the combination of both and the mean of Sen slopes was estimated. With the mean value of each patch we performed a two way ANOVA to determine whether there existed differences between cities and land cover classes. This conservative analysis (data were clumped) prevented problems of autocorrelation between observations.

After inspecting the general patterns of productivity trend we performed regression analyses of these trends to identify plausible causes. In these analyses pixels were clumped based on the identity of the cities. We analyzed the association of productivity trend with urban features (initial size, expansion and population growth) and on climate features (mean annual temperature, annual rainfall, and de Martonne aridity index).

3. Results

All the cities expanded their area between 2000 and 2012, ranging from less than 1% (Clorinda) to more than 50% (Jujuy, Table 1). Population growth in the same period ranged from less than 10% (Clorinda and Tucuman) to more than 25% (La Rioja).

Mean annual expansion of cities showed positive correlation with the initial size of the urban area ($r = 0.796$) and with population growth ($r = 0.599$).

Mean productivity decreased in all the cities and the annual rate of decrease was more related to the identity of the city than to the land cover classification (urban, expansion, periphery, Fig. 2). The average trend in productivity ranged between $-2.54\%\ \text{year}^{-1}$ in Metán to $-0.22\%\ \text{year}^{-1}$ in Concepción. In contrast, the range was much tighter between conditions; it was $-1.37\%\ \text{year}^{-1}$ in urban areas and -1.21% in the periphery. We found significant differences in the trend of productivity between cities ($F = 31.35$; $df = 11$; $p < 0.001$), but no significant differences were observed between classes ($F = 0.74$; $df = 2$; $p = 0.48$).

There was almost no association between the time trend in vegetation productivity and urban features (original size, expansion area and population growth, Fig. 3). In contrast, there was a strong negative association between the mean annual temperature of cities and the trend in productivity ($r^2 = 0.456$).

4. Discussion

Our results show that the main cities of northern Argentina have grown rapidly in population and in urban area, which is concordant with urbanization and urban expansion scenarios proposed for middle size cities in developing countries (United Nations

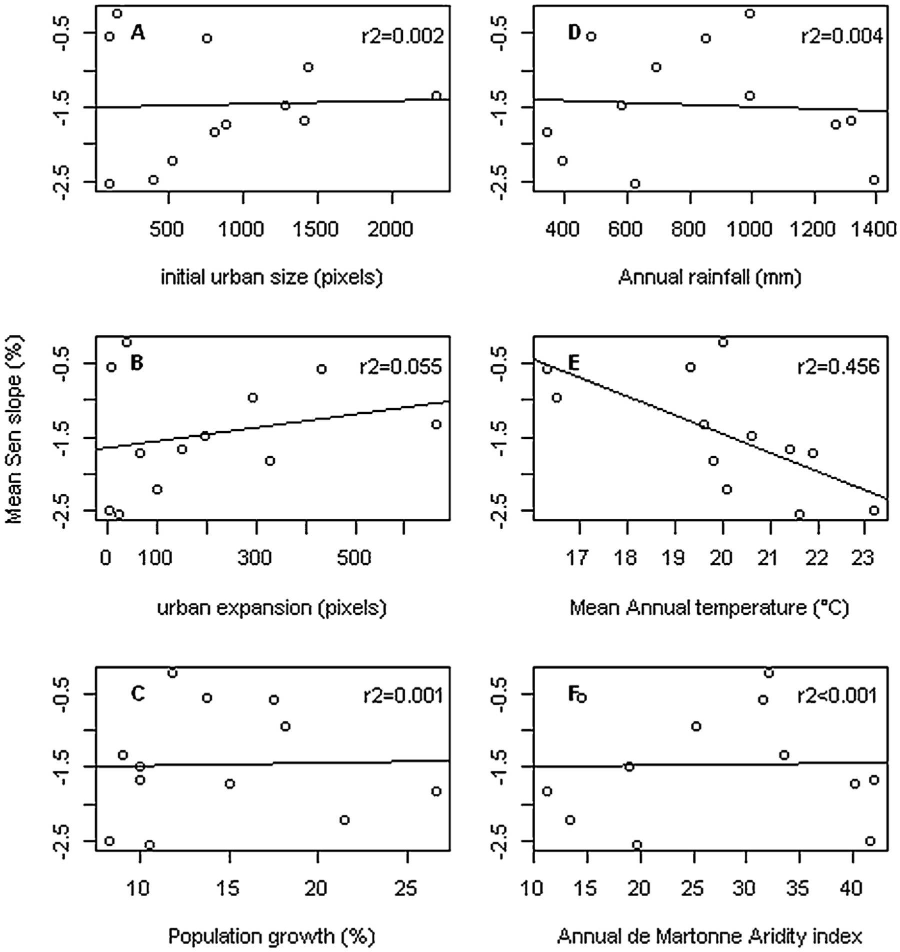

Fig. 3. Relation between explanatory variables and mean percent Sen slope of vegetation productivity based on cities. Regression lines and squared r are represented in each panel. A–C represent variables related to the urban dynamics (initial size, urban expansion and population growth). D–F represent climate variables in the cities (annual rainfall, mean annual temperature and annual de Martonne aridity index).

Table 1
Urban and population growth during the last decade in the study sites.

ID	Period	Initial size (km^2)	Final size (km^2)	Area expansion (%)	Mean annual expansion (Km^2)	Population 2001	Population 2010	Population growth (%)
Catamarca	2003–2013	33.38	39.63	18.73%	0.625	142,700	173,400	21.51
Clorinda	2005–2013	25.38	25.56	0.74%	0.023	78,700	85,200	8.26
Concepción	2002–2012	10.06	11.81	17.39%	0.175	75,400	84,300	11.80
Corrientes	2002–2013	49.13	53.06	8.02%	0.358	333,400	383,500	15.03
Güemes	2003–2010	6.63	7.00	5.66%	0.054	42,300	48,100	13.71
Jujuy	2002–2013	47.69	74.56	56.36%	2.443	238,400	280,000	17.45
La Rioja	2002–2013	50.81	71.31	40.34%	1.864	150,400	190,500	26.66
Metan	2003–2012	6.94	8.44	21.62%	0.167	39,100	43,200	10.49
Resistencia	2002–2013	88.63	97.88	10.44%	0.841	369,200	406,200	10.02
Salta	2002–2013	90.06	108.38	20.33%	1.665	476,200	562,600	18.14
S. del Estero	2004–2013	80.69	93.00	15.26%	1.368	247,400	272,200	10.02
Tucumán	2002–2014	143.94	185.50	28.88%	3.464	537,900	586,200	8.98

Report, 2014). These patterns show that the analyzed cities have experienced a rapid population growth between 2000 and 2010. Generally, the patterns of urban dynamics associated to population growth can be seen as a mixture of expansion and densification. Nevertheless, complementary analyses show a strong association between the initial size of the urban area and the proportional change of population density for the period 2001–2010, suggesting that urban dynamics is dominated by low density expansion over urban densification, especially for bigger (probably more dense and rich) cities (Fig. 4).

Associated to this, the trend of vegetation productivity through time is more affected by the location of cities (i.e. climate and environmental conditions) than by the land cover classification (urban, expansion and periphery). This suggests that the trend in vegetation productivity is controlled more by local environmental conditions rather than by the process of vegetation removal or replacement associated to land cover change produced by the expansion of cities. For example we observed that the decreasing trend was more important in cities that had less vegetation at the

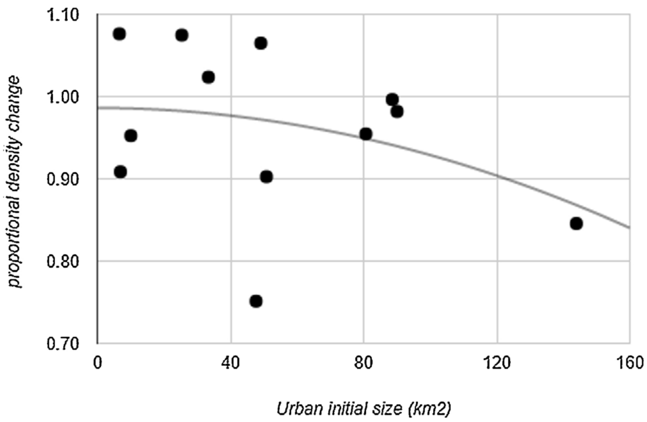

Fig. 4. Relationship between initial size of the urban area and proportional change of population density.

beginning. Moreover, land cover classes were not associated with the trends in productivity.

In contrast, the decline in productivity observed in urban areas was associated with average productivity, suggesting that climate warming could be the main process affecting the decrease of productivity. Photosynthetic activity (PA) is controlled both by water availability and by temperature. In general there is a monotonic increase of PA with an increase of water availability. In contrast, the response of PA to temperature may not be monotonic and it might interact with water availability: PA increases monotonically with temperature until water availability limits PA and stomata tend to close when water loss cannot be afforded by plants. In the studied cities, temperatures are relatively homogeneous so the vegetation productivity was linearly (and positively) associated with water availability. This productivity decreased through time in most of the region, even in the locations that are far from urban areas, but it increased slightly in montane areas (data not shown), where temperatures tend to be lower. Thus, climate warming could explain the decrease in productivity. The counterintuitive finding that productivity decline was more marked in urban class than in expansion class (where the likelihood of vegetation loss is greater) could be associated to the process of urban heat islands associated to the densification of built-up areas.

Since most studies that focus on vegetation productivity use single NDVI images, they find that their results are highly sensitive to the date of image acquisition. Since cumulative photosynthetic activity obtained from remotely sensed data is not a direct measure of primary production, the values retrieved through this method could be used for comparative purposes but not as an absolute record of primary productivity. When performing trend analysis of high temporal frequency remotely sensed data (e.g. daily) post-classification comparison method are a poor cost-effective analysis. Vegetation functioning analyses require high temporal resolution data and long term analysis to capture those changes through growing seasons, for different years. To achieve this, the methodology used must complement the ability to process a large amount of temporal records with a capacity to reconstruct phenological patterns and synthesize results. The use of a phenological curve seems to provide a more complete view of the process. Moreover, other parameters of the curve (e.g. beginning and end of the growing season) could be useful to understand the intermediate processes that might be affected in the change of productivity through time.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2016.04.005.

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