Landscape and Urban Planning 105 (2012) 149–159

Contents lists available at SciVerse ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

# Urbanization diversifies land surface phenology in arid environments: Interactions among vegetation, climatic variation, and land use pattern in the Phoenix metropolitan region, USA

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A R T I C L E I N F O

*Article history:*
Received 22 February 2011
Received in revised form 7 December 2011
Accepted 21 December 2011
Available online 10 January 2012

*Keywords:*
Vegetation phenology
Land surface phenology
Sonoran desert
Urban–rural gradient
Remote sensing
MODIS NDVI

A B S T R A C T

Urbanization transforms vegetation pattern and ecosystem processes which are controlled primarily by climate in desert regions. The objective of this study was to investigate how urbanization affects vegetation phenology and its coupling with climate in the Phoenix metropolitan region, USA. Our analysis of Normalized Difference Vegetation Index (NDVI) time-series reveals a complex pattern of land surface phenology in response to urbanization. Croplands and urbanized areas show growth multimodality, which is usually found in riparian areas of the region but absent in the native desert. Agriculture is characterized by the shortest growth length and fastest greening and senescing rates. Conversely, urban vegetation stays photosynthetically active for longer periods. Desert NDVI is regulated by 3–5 month accumulated precipitation, but riparian vegetation is uncorrelated with rainfall. NDVI spatial patterns are best predicted by climatic variables near the peak of annual growth. Spring and summer NDVI is in better agreement with precipitation accumulated over longer time periods, while early autumn growth is strongly correlated with immediate and one-month rainfall. Temperature correlates negatively with desert but positively with riparian NDVI. Managed vegetation growth is decoupled from precipitation and completely unsynchronized with natural desert vegetation. Overall, urbanization has resulted in a greater phenological diversity that is not in sync with climatic variability. Our findings provide new insights into the interactions among vegetation growth, climate variability, and urbanization in dry lands.



## 1. Introduction

Urbanization is a key driver of human-induced environmental changes (Grimm et al., 2008; Kareiva et al., 2007). In particular, primary productivity is strongly affected by urban development (Buyantuyev and Wu, 2009; Imhoff et al., 2004), raising concerns with the sustainability of urban regions, which can only be achieved by balancing environmental protection, economic development, and social wellbeing (Wu, 2008). Yet, little research has been directed to understanding the effects of urbanization on ecosystem functioning until recently (Grimm et al., 2008). A number of studies have shown that changes in vegetation phenology – environment-mediated chronology of recurring phases of vegetation development – are indicative of ecological and environmental effects of urbanization and global climate change (Badeck et al., 2004; Lieth and Schwartz, 1997; Menzel, 2002; Morisette et al., 2009; Peñuelas and Filella, 2001; White et al., 2003).

Urban land-cover transformations affect plant phenology most directly by modifying hydrological regime, local and regional climates, and vegetation cover and species composition. Urban hydrology, characterized by increased runoff and reduced groundwater (Pickett et al., 2011), is likely to have significant repercussions on phenology in cities. Excessive heating in urban areas may promote earlier spring growth while simultaneously shortening the overall growing period. Urban vegetation frequently includes exotic species that may exhibit phenological patterns different from native plants. Furthermore, urban phenology is likely dependent on human preferences in shaping urban landscapes (e.g., food crops, city shade trees, golf courses, etc.). Agricultural development and urbanization in arid and semi-arid regions, for example, can often boost primary productivity by introducing productive plant communities sustained by irrigation and nutrient supplementation (Buyantuyev and Wu, 2009; Imhoff et al., 2004).

Recent studies that focused on urban-to-rural differences in phenology have emphasized the warming effect, which has been consistently shown to advance the onset of flowering in cities of Europe (Mimet et al., 2009; Roetzer et al., 2000) and China (Lu et al.,

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doi:10.1016/j.landurbplan.2011.12.013

2006), and accelerate the date of leaf emergence in cities of North America (Fisher et al., 2006). Remote-sensing analyses revealed earlier green-up, delayed dormancy, and the extension of growing period by 15 days in some cities of the Northern Hemisphere (Zhang et al., 2004). On the other hand, effects of precipitation on phenological shifts in response to climate change have been overlooked (Peñuelas et al., 2004). In arid regions, however, water availability is the principal trigger of phenology (Beatley, 1974; Bowers and Dimmitt, 1994; Noy-Meir, 1973; Schwinning et al., 2004) and the ultimate determinant of distribution and composition of vegetation (Noy-Meir, 1973). Unlike temperature, the spatial and temporal distribution of rainfall in arid regions is highly variable and relatively unpredictable. This makes it difficult to generalize about connections between rainfall and vegetation growth. Furthermore, from the ecosystem functioning perspective, the function of rainfall as the trigger of ecological processes is determined by hydrological and soil properties (Schwinning et al., 2004). Considering these complex interactions between precipitation and vegetation dynamics in arid regions, more research is needed to understand how urbanization may affect water availability and phenological patterns in these areas.

Recent phenological studies have utilized remote sensing, permitting observation of vegetation patterns of large areas. This approach, often referred to as land surface phenology (de Beurs and Henebry, 2004), is fundamentally different from ground-based observations in that satellite sensors are only capable of capturing aggregate, ecosystem-level signals of greenness (Reed et al., 1994). Most such studies have relied on the Normalized Difference Vegetation Index (NDVI), which is based on the property of green vegetation to strongly absorb red and reflect near-infrared wavelengths (Huete et al., 1999), as a proxy for fraction of photosynthetically active radiation absorbed by plants (APAR) (Running et al., 2000). NDVI time series are increasingly used to monitor vegetation dynamics (Bradley et al., 2007; Moody and Johnson, 2001). When the index is related to climatic variables, important details of climate-ecosystem interactions can be inferred (Justice and Hiernaux, 1986; Malo and Nicholson, 1990; Nicholson and Farrar, 1994; Peters and Eve, 1995; Tucker et al., 1985; Wang et al., 2001; Zhang et al., 2005). These studies have found linear or log-linear rainfall-NDVI relationships and the existence of time lags at which vegetation most strongly responds to precipitation.

Phenological metrics, such as start, end, and length of growing season, are important indicators of vegetation responses to climatic fluctuations and urbanization-induced land-cover transformations. When changes in phenological metrics and their environmental determinants are analyzed along urban-to-rural gradients, effects of urbanization on phenology can be quantified. The gradient concept, originally developed in plant community ecology, has been adopted in ecosystem studies (Vitousek and Matson, 1991) and in urban ecology (Luck and Wu, 2002; McDonnell and Pickett, 1990). For this study we defined the urban–rural gradient by conceptually arranging land-cover classes along their degree of anthropogenic modification.

Detailed studies of vegetation phenology and its triggering factors along urban-to-rural gradients are extremely rare, especially in arid regions (Neil and Wu, 2006). In this study we investigated ecosystem level vegetation phenological patterns (land surface phenology), their responses to climate drivers, and contrasted native vegetation types with urban and agricultural vegetation in the Phoenix metropolitan region, USA. Our study addressed the following research questions: (1) How does land surface phenology vary between major vegetation types in the area and along the urbanization gradient? (2) Are there any differences in responses of land surface phenology to multiscale climatic triggers along the urbanization gradient? (3) Can climate patterns predict spatial and temporal heterogeneity of phenology and whether optimal time scales exist at which predictions are most accurate?

## 2. Materials and methods

### 2.1. Study area

Phoenix (Fig. 1) is characterized by hot and dry (mean annual rainfall < 200 mm) climate with bimodal annual precipitation. Winter rain from frontal systems provides the majority of moisture to this area. About 40% of precipitation occurs as mid- to late summer monsoonal rain that mostly falls in the mountains northeast of Phoenix. Some of the rainstorms reach lower elevations to the west resulting in very intense localized rainfall events (Comrie and Glenn, 1998). Historically, this area was dominated by two subdivisions of the Sonoran desert scrub – the 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 the Lower Colorado River with creosotebush-bursage (*Larrea tridentata* and *Ambrosia dumosa*) series (Brown, 1994). Native riparian vegetation is characterized by riparian scrubland along minor drainages and mesquite (*Prosopis glandulosa*) and cottonwood-willow (*Populus fremontii*, *Salix sp.*, and invasive *Tamarix ramosissima*) deciduous forest and woodlands along major waterways.

Irrigated agriculture dating back to 500–700 AD developed mostly at the expense of the creosote-bursage desert and riparian ecosystems. After its designation as the capital of Arizona in 1911, Phoenix grew rapidly to accommodate the current population of more than 4 million people and became the fourteenth largest U.S. metropolitan area (US Census Bureau, 2010).

### 2.2. NDVI data processing and vegetation phenology analysis

Moderate resolution Imaging Spectroradiometer (MODIS) instruments aboard TERRA/AQUA satellites have a revisit period of 1–2 days and collect data in 36 spectral channels at three spatial resolutions (250, 500, and 1000 m). The standard MODIS 250-m NDVI (MOD13Q1) product is derived from TERRA reflectance data corrected for molecular scattering, ozone absorption and aerosols. However, reflectance images used for NDVI derivation are not adjusted to nadir and Sun angles with the use of Bidirectional Reflectance Distribution Function (BRDF) models, such as another product, MCD43A4, available at 500-m resolution. Despite this drawback of MOD13Q1, we considered the importance of its higher spatial resolution critical for understanding spatial heterogeneity within urban regions. We obtained 250-m NDVI images for 2000–2005 and used the TIMESAT method (Eklundh and Jönsson, 2009) to de-noise data, fit smooth curves, and extract phenological metrics. The method uses three alternative techniques based on least-squares fits to the upper envelope of NDVI time-series: fitting with local polynomial functions (Savitsky-Golay filtering), weighted fitting to asymmetric Gaussian and double logistic model functions (Jönsson and Eklundh, 2002). The results obtained by removing NDVI spikes larger than two times the standard deviation and fitting local polynomial functions most closely corresponded to raw NDVI during method testing and were preferred in our study. To minimize the negative bias in NDVI data three adaptation runs were executed with search window set to 4, 3, and 2 consecutive NDVI values. The start of growth was defined as the time for which the left edge of NDVI curve has increased 20% of the seasonal amplitude from the left minimum level, while growth end was defined as the time for which the curve has decreased to the 20% level measured from the right minimum level (Eklundh and Jönsson, 2009).

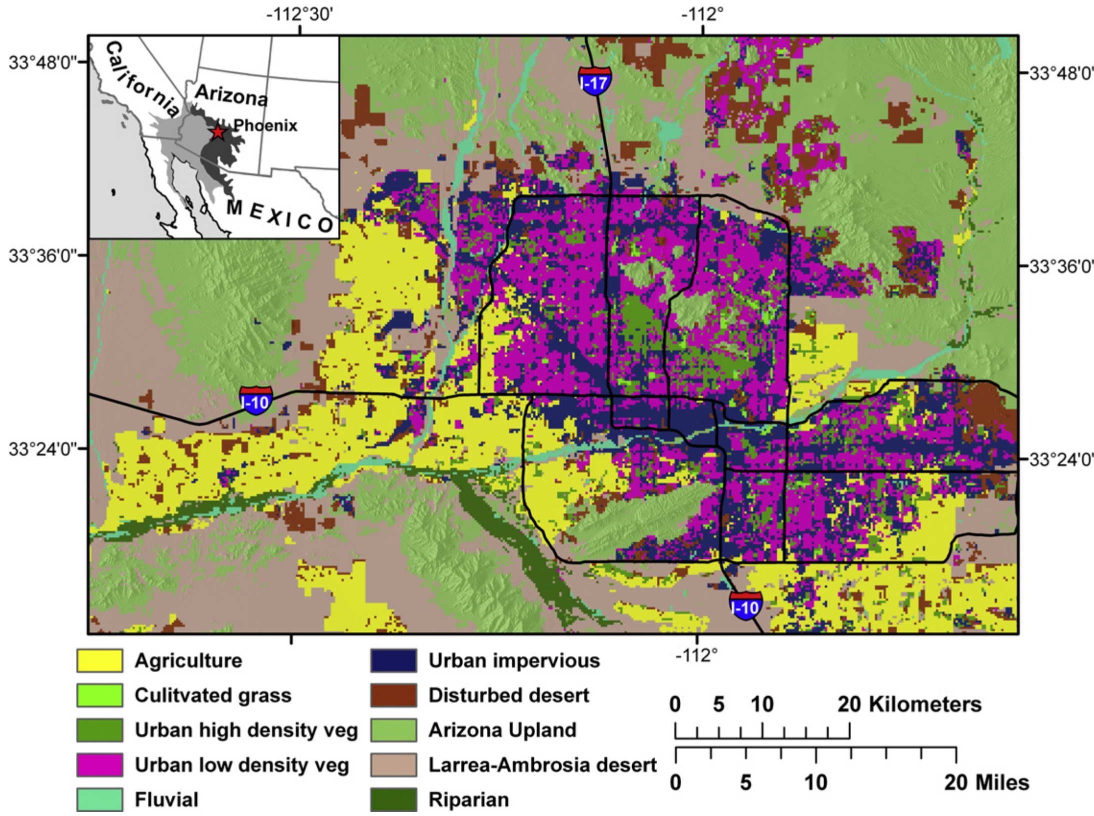


**Fig. 1.** Study area land cover map (2000). Lighter gray color in the inset map represents the Lower Colorado River and darker gray – the Arizona Upland subdivisions of Sonoran Desert. Black lines are highways.

### 2.3. Climate data

Surfaces of climate variables were constructed using data from five major national, state, and local meteorological networks: Arizona Meteorological Network (AZMET), Flood Control District of Maricopa County Automated Local Evaluation in Real-Time (ALERT) Weather Station Network, Phoenix Real-time Instrumentation for Surface Meteorological Studies (PRISMS), Remote Automated Weather Station (RAWS) Network, and the National Weather Service (NWS) network. Precipitation grids for each period were interpolated from the total of 305 sensors by analyzing empirical semivariograms and employing ordinary kriging. Air temperature (55 stations) was gridded using the approach of Kato and Yamaguchi (2005) by first applying the 6.5 K/km environmental lapse rate and converting actual observations into sea level temperatures that were krigged to produce sea-level temperature surfaces. We then derived final temperature grids by inverting the environmental lapse rate to adjust for elevation derived from DEM (USGS National Elevation Dataset). Scale translation of climate data was performed by aggregating daily observations to match the temporal and spatial resolution of MODIS data.

### 2.4. Land use and land cover (LULC)

The land-cover map (Fig. 1) is a composite of two existing Landsat-based classifications: the general reference LULC map produced using Stefanov, Ramsey, and Christensen (2001) expert model and the Southwest Region GAP (SWReGAP) classification (Lowry et al., 2005). The merger classification was created in ArcInfo GIS by using a set of reclassification rules and cell recoding. Urban and agricultural land-cover classes were retained from the general reference classification while its undisturbed desert class was replaced by natural vegetation classes from the SWReGAP map. We also performed class consolidations to eliminate low-accuracy classes from both maps. Examples of consolidated classes are agriculture (anthropogenic) and riparian (natural). The final land cover map depicts two major subdivisions of Sonoran desert, the Arizona Upland and the Lower Colorado River (labeled as Larrea-Ambrosia desert on our map) riparian areas, and ecologically relevant urban classes.

### 2.5. Analysis of temporal and spatial relationships between NDVI and climate variables

Bivariate linear correlations were analyzed in two ways. First, Spearman's rank correlation coefficients were computed by relating single-pixel NDVI at every biweekly period to a climatic variable at the same single-pixel location and for the same biweekly period. Correlations were then computed for each corresponding NDVI-climate variable pair with temporal lags for temperature progressively increased and precipitation progressively aggregated (accumulated) (Table 1, Fig. 2). Overall, we considered four biweekly time lags (lag1, lag2, lag3, and lag4) for temperature and eleven accumulation periods (0, 0–1, 0–2, 0–3. . .0–10) for rainfall, where 0–10 equals 5-month precipitation (Table 1).

Second, we conducted spatial correlation analysis by overlaying pairs of NDVI and climate grids stratified according to land-cover categories and extracting all corresponding pairs of pixel values. Each set of extracted pairs was used to compute correlation coefficient and allowed us to evaluate the agreement between spatial patterns of NDVI and precipitation and temperature (Table 2, Fig. 2). Spatial correlations were also computed for the four progressively increased temporal lags and eleven accumulation periods. We did not apply Bonferroni's correction for multiple comparisons because we only sought relative ordinal relationships among these correlations, without specific claims of statistical

**Table 1**
Calculation of temporal correlations between NDVI and rainfall/temperature ($T^\circ$) for a single pixel ($x_1y_1$) location with no time lag, two temporal lags, and three rainfall accumulation periods (for definitions see Fig. 2). *Note*: In total we considered four bi-weekly time lags (lag1, lag2, lag3, and lag4) for temperature and eleven accumulation periods (0, 0–1, 0–2, 0–3 . . . 0–10) for rainfall.

| | NDVI | Lag0 $T^\circ$ | Lag1 $T^\circ$ | Lag2 $T^\circ$ | 0–1 rainfall | 0–2 rainfall | 0–3 rainfall |
|---|---|---|---|---|---|---|---|
| 1 | NDVI @ $t_1$ | $T^\circ$ @ $t_1$ | – | – | – | – | – |
| 2 | NDVI @ $t_2$ | $T^\circ$ @ $t_2$ | $T^\circ$ @ $t_1$ | – | Rain @ $t_1 + t_2$ | – | – |
| 3 | NDVI @ $t_3$ | $T^\circ$ @ $t_3$ | $T^\circ$ @ $t_2$ | $T^\circ$ @ $t_1$ | Rain @ $t_2 + t_3$ | Rain @ $t_1 + t_2 + t_3$ | – |
| 4 | NDVI @ $t_4$ | $T^\circ$ @ $t_4$ | $T^\circ$ @ $t_3$ | $T^\circ$ @ $t_2$ | Rain @ $t_3 + t_4$ | Rain @ $t_2 + t_3 + t_4$ | Rain @ $t_1 + t_2 + t_3 + t_4$ |
| : | : | : | : | : | : | : | : |
| $n$ | NDVI @ $t_n$ | $T^\circ$ @ $t_n$ | $T^\circ$ @ $t_{n-1}$ | $T^\circ$ @ $t_{n-2}$ | Rain @ $t(_{n-1} + t_n$ | Rain @ $t(_{n-2} + t_{n-1} + t_n$ | Rain @ $t(_{n-3} + t_{n-2} + t_{n-1} + t_n$ |

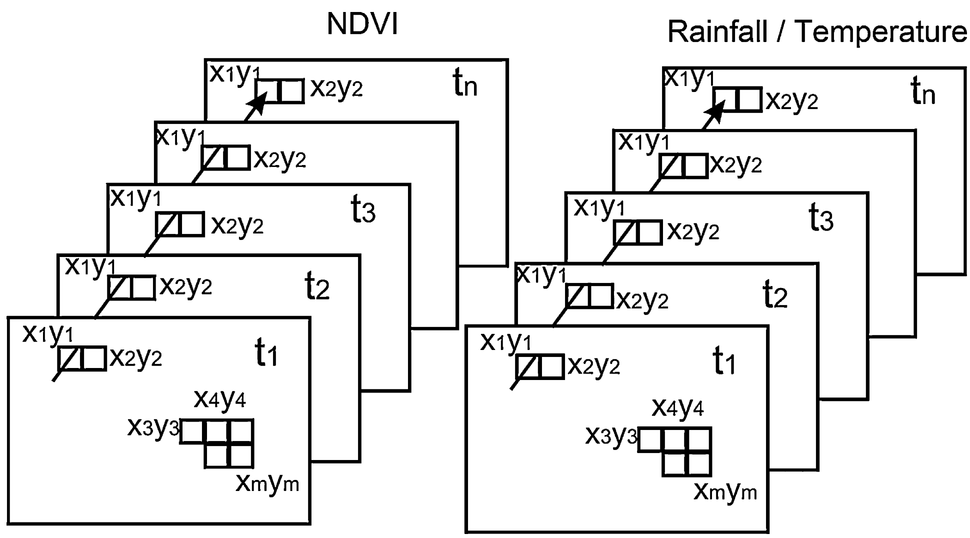


**Fig. 2.** Computation of temporal and spatial correlations between NDVI and rainfall/temperature. $x_1y_1, x_2y_2 \ldots x_my_m$ are corresponding single pixel locations that belong to the same land cover class. $t_1, t_2 \ldots t_n$ are bi-weekly (16-day) periods ($n = 115$ for 2001–2005). See Tables 1 and 2.

**Table 2**
Calculation of spatial correlations between NDVI at time $t = 3$ and rainfall of the same time period (lag0), one preceding bi-weekly period (lag1) and two rainfall accumulation periods (for definitions see Fig. 2). *Note*: In total we considered four bi-weekly time lags (lag1, lag2, lag3, and lag4) for temperature and eleven accumulation periods (0, 0–1, 0–2, 0–3 . . . 0–10) for rainfall.

| | NDVI | Lag0 $T^\circ$ | Lag1 $T^\circ$ | 0–1 rainfall | 0-2 rainfall |
|---|---|---|---|---|---|
| 1 | NDVI @ $t_3$ @ $x_1y_1$ | $T^\circ$ @ $t_3$ @ $x_1y_1$ | $T^\circ$ @ $t_2$ @ $x_1y_1$ | Rain @ $t_2 + t_3$ @ $x_1y_1$ | Rain @ $t_1 + t_2 + t_3$ @ $x_1y_1$ |
| 2 | NDVI @ $t_3$ @ $x_2y_2$ | $T^\circ$ @ $t_3$ @ $x_2y_2$ | $T^\circ$ @ $t_2$ @ $x_2y_2$ | Rain @ $t_2 + t_3$ @ $x_2y_2$ | Rain @ $t_1 + t_2 + t_3$ @ $x_2y_2$ |
| 3 | NDVI @ $t_3$ @ $x_3y_3$ | $T^\circ$ @ $t_3$ @ $x_3y_3$ | $T^\circ$ @ $t_2$ @ $x_3y_3$ | Rain @ $t_2 + t_3$ @ $x_3y_3$ | Rain @ $t_1 + t_2 + t_3$ @ $x_3y_3$ |
| 4 | NDVI @ $t_3$ @ $x_4y_4$ | $T^\circ$ @ $t_3$ @ $x_4y_4$ | $T^\circ$ @ $t_2$ @ $x_4y_4$ | Rain @ $t_2 + t_3$ @ $x_4y_4$ | Rain @ $t_1 + t_2 + t_3$ @ $x_4y_4$ |
| : | : | : | : | : | : |
| $m$ | NDVI @ $t_3$ @ $x_my_m$ | $T^\circ$ @ $t_3$ @ $x_my_m$ | $T^\circ$ @ $t_2$ @ $x_my_m$ | Rain @ $t_2 + t_3$ @ $x_my_m$ | Rain @ $t_1 + t_2 + t_3$ @ $x_my_m$ |

significance. All correlation coefficients significant at $p < 0.05$ were visually compared using graphs and maps. Statistical analyses were performed using ArcInfo workstation and SAS JMP 7.0.2 software.

## 3. Results

### 3.1. Phenological differences between land covers and along the urbanization gradient

Total number of growing seasons during the 5-year period (2001–2005) varied considerably (Fig. 3). Nearly 10% of cultivated grasses had more than eight growing seasons, which corresponded to two or more seasons a year. More than 50% of croplands and riparian ecosystems were characterized by annual bi-modality (at least one year with two growing seasons). Desert vegetation mostly exhibited one growing season a year (with one year of no growth), and had no more than four growing seasons in this 5-year period (Fig. 3). Because growth in most land covers did

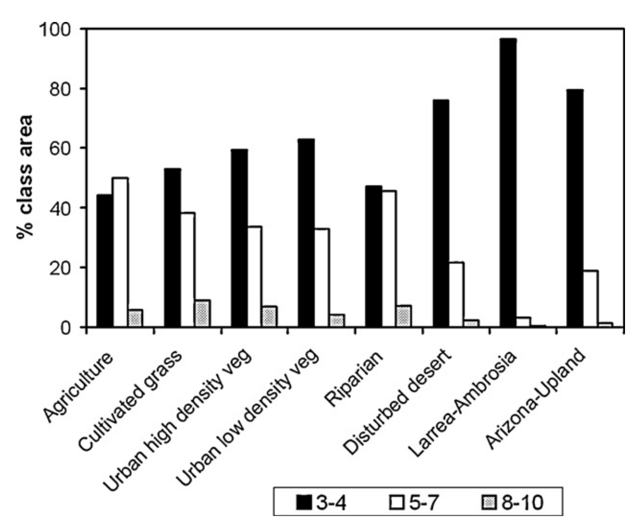


**Fig. 3.** Distribution of the total number of growing seasons during 2001–2005.

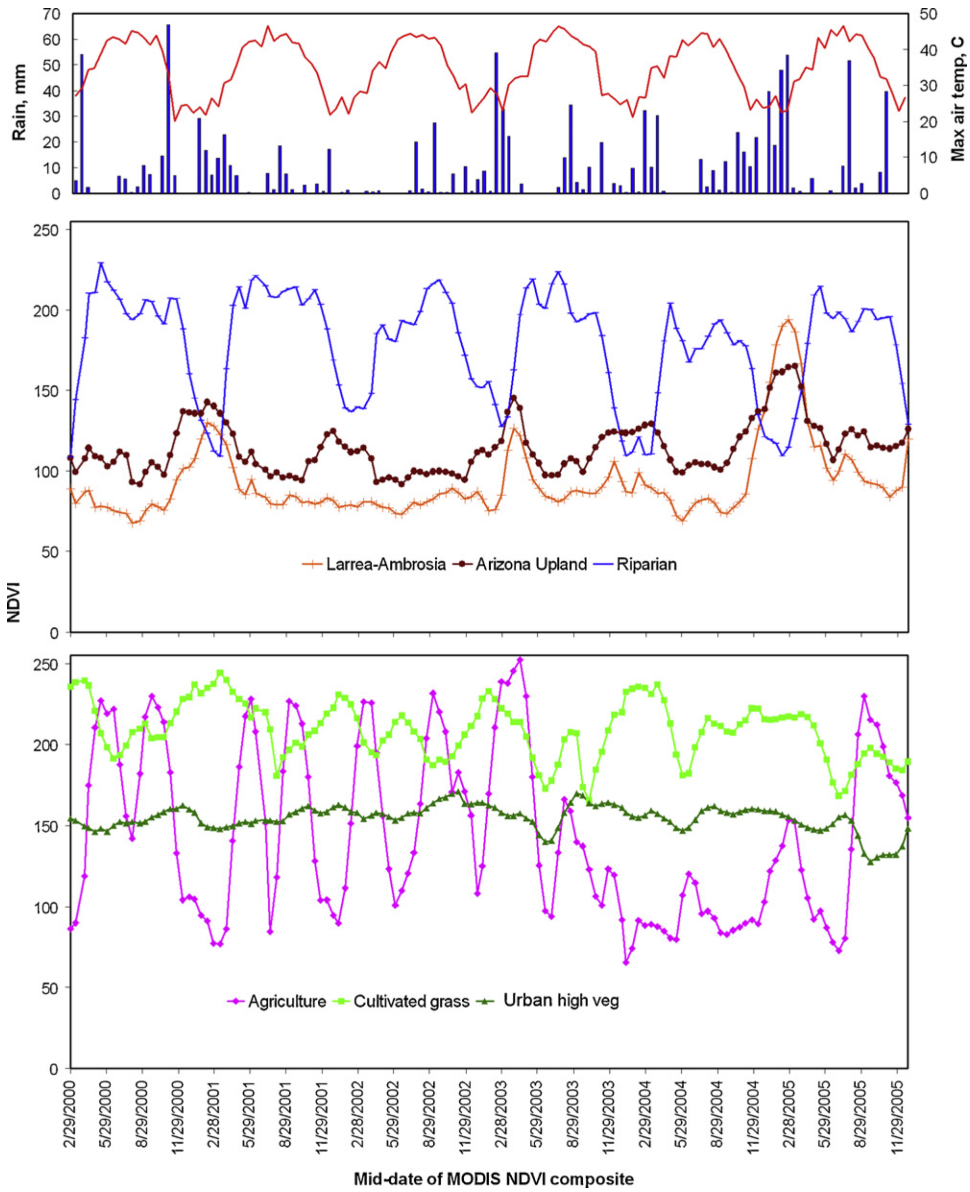


**Fig. 4.** Filtered NDVI temporal curves extracted for point locations in six different land covers. Time-series of bi-weekly precipitation (blue bars) and maximum air temperature (red line) are shown at the figure top. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

not follow the calendar year, and to accommodate for the existence of long growing seasons and growth bi-modality (Fig. 4), phenological metrics shown in Table 3 were computed for four overlapping 1.5-year periods. For convenience, seasons here are numbered consecutively throughout the entire 5-year period. With the exception of native desert vegetation, more than three seasons could take place within any given calendar year (e.g., 2001). Phenological metrics illustrate short growing seasons in croplands and longer growth of riparian, urban vegetation, and cultivated grasses (Table 3). In the dry year of 2002, however, growth was longer for both urban and desert vegetation. No consistent pattern is detected in areas with more than one annual growing season, although seasons that started in early spring were longer in croplands and those started at other times were longer in the urban land cover of high density vegetation (Table 3).

Untransformed plant communities demonstrated predictable seasonal growth cycles with peaks in early spring in the desert and early summer to early autumn in riparian ecosystems (Fig. 4). Desert growth can start anytime between early August and November and end in early summer, but it can cease as early as late April in the Larrea-Ambrosia desert and mid-May in the Arizona Upland (Table 3). Riparian growth is spatially heterogeneous and correlates with air temperature (Figs. 3 and 4). Riparian communities with growth bi-modality green up in mid-February and defoliate in July. The shorter second annual growing season often coincides with growth in the desert (Table 3). Riparian forests with single growing season green up in early March (delayed during droughts) and end growing in January (Table 3).

Urban and agricultural vegetation is characterized by high greenness with urban communities being the least temporally variable. Annual variation of agricultural NDVI is very high, while NDVI of cultivated grasses never drops below a certain greenness level. Beginning and end of growth of managed vegetation are closer in time to riparian than to desert vegetation suggesting year-round water availability (Table 3).

**Table 3**
Medians of phenological metrics for selected land cover classes. *Notes*: DOYS and DOYE are start and end of growing seasons (day of year); L is growing season length (days); G is the rate of greening up calculated by dividing the difference between the left 20% and 80% NDVI levels and the corresponding time difference; S is the rate of senescing calculated as the absolute value of the ratio of the difference between the right 20% and 80% levels of NDVI and the corresponding time difference.

| | 2001 (1st) | | | | | 2001–2002 (2nd) | | | | | 2001–2002 (3rd) | | | | | 2002–2003 (4th) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S |
| Urban low density veg | 62 | 207 | 144 | 2 | 2 | 163 | 46* | 256 | 1 | 1 | 243 | 31* | 155 | 1 | 1 | 121 | 356 | 188 | 2 | 2 |
| Urban high density veg | 46 | 190 | 145 | 3 | 2 | 146 | 35* | 274 | 2 | 2 | 231 | 29* | 166 | 2 | 3 | 110 | 354 | 210 | 2 | 3 |
| Cultivated grass | 39 | 197 | 143 | 6 | 4 | 216 | 77* | 263 | 3 | 4 | 236 | 26* | 158 | 4 | 3 | 74 | 257 | 164 | 4 | 4 |
| Agriculture | 94 | 241 | 154 | 11 | 9 | 154 | 13* | 216 | 9 | 8 | 276 | 79* | 155 | 8 | 7 | 104 | 332 | 174 | 6 | 6 |
| Arizona upland | – | – | – | – | – | 275 | 132* | 228 | 1 | 2 | – | – | – | – | – | – | – | – | – | – |
| Larrea-Ambrosia | – | – | – | – | – | 275 | 116* | 215 | 1 | 1 | – | – | – | – | – | – | – | – | – | – |
| Riparian | 46 | 200 | 151 | 6 | 3 | 65 | 29* | 322 | 7 | 9 | 234 | 39* | 166 | 3 | 8 | 134 | 4* | 226 | 3 | 5 |

| | 2002–2003 (5th) | | | | | 2003 (6th) | | | | | 2003–2004 (7th) | | | | | 2003–2004 (8th) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S |
| Urban low density veg | 153 | 47* | 302 | 2 | 2 | 60 | 196 | 140 | 2 | 1 | 178 | 108* | 289 | 2 | 2 | 233 | 78* | 176 | 2 | 2 |
| Urban high density veg | 127 | 53* | 307 | 2 | 3 | 56 | 190 | 140 | 3 | 3 | 188 | 64* | 273 | 2 | 3 | 222 | 24* | 168 | 3 | 4 |
| Cultivated grass | 192 | 144* | 276 | 4 | 4 | 60 | 210 | 147 | 4 | 3 | 202 | 63* | 268 | 3 | 5 | 247 | 34* | 152 | 4 | 5 |
| Agriculture | 139 | 40* | 248 | 8 | 7 | 60 | 219 | 152 | 6 | 7 | 184 | 25* | 215 | 6 | 7 | 276 | 117* | 157 | 6 | 6 |
| Arizona upland | 216 | 184* | 331 | 2 | 5 | – | – | – | – | – | 243 | 154* | 272 | 2 | 3 | – | – | – | – | – |
| Larrea-Ambrosia | 227 | 186* | 315 | 2 | 5 | – | – | – | – | – | 229 | 138* | 260 | 2 | 2 | – | – | – | – | – |
| Riparian | 89 | 17* | 293 | 6 | 9 | 58 | 198 | 145 | 6 | 4 | 74 | 16* | 304 | 6 | 13 | 229 | 24* | 157 | 4 | 9 |

| | 2004 (9th) | | | | | 2004–2005 (10th) | | | | | 2004–2005 (11th) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S | DOYS | DOYE | L | G | S |
| Urban low density veg | 112 | 282 | 144 | 2 | 2 | 181 | 116* | 256 | 2 | 2 | 337 | 153* | 165 | 2 | 2 |
| Urban high density veg | 63 | 233 | 142 | 3 | 3 | 169 | 88* | 280 | 2 | 3 | 328 | 139* | 157 | 4 | 4 |
| Cultivated grass | 59 | 219 | 152 | 5 | 4 | 180 | 102* | 259 | 4 | 4 | 304 | 120* | 163 | 3 | 5 |
| Agriculture | 95 | 281 | 161 | 7 | 6 | 168 | 74* | 216 | 10 | 10 | 349 | 153* | 162 | 10 | 10 |
| Arizona upland | – | – | – | – | – | 308 | 159* | 219 | 8 | 9 | – | – | – | – | – |
| Larrea-Ambrosia | – | – | – | – | – | 320 | 159* | 206 | 11 | 13 | – | – | – | – | – |
| Riparian | 63 | 211 | 147 | 7 | 3 | 68 | 16* | 297 | 9 | 9 | 332 | 151* | 151 | 6 | 7 |

* Indicates the end of growth occurred in the next calendar year (if a growing season spans two years).

Agricultural and riparian vegetation is characterized by the highest rate of greening and senescing. These metrics are highly variable in the desert reaching the maximum amplitude in Larrea-Ambrosia communities and demonstrating a 10-fold increase during wetter periods (Table 3).

### *3.2. Responses of leaf phenology to multiscale climatic triggers along the urbanization gradient*

Strong and moderate positive NDVI-rainfall correlations are common in the Arizona Upland and Larrea-Ambrosia desert while the rest of the area is either correlated weakly or completely uncorrelated. Correlation strength tends to increase with increasing rainfall accumulation, especially in areas occupied by Larrea-Ambrosia communities west and north of Phoenix (Figs. 5 and 6). Spatially averaged correlation increases substantially when related to a 3-month rainfall. Correlation continues to slowly increase for Larrea-Ambrosia communities, but it levels off for the Arizona Upland (Fig. 6A). Urban and agricultural land covers are essentially uncorrelated with precipitation and insensitive to the increase of rainfall accumulation (Fig. 6A).

Response patterns of NDVI to minimum and maximum air temperature are very similar, so only the results for maximum temperature are presented. Correlation maps reveal more heterogeneous patterns within a given urban and agricultural land cover type, which are characterized by significant and frequent changes in values across space and higher standard deviation of correlations for these land covers. Negative correlations predominate spatially and occur in all areas with natural vegetation, except riparian. Positive correlations are found in 50% of agricultural and urban dense vegetation and 30–40% of cultivated grasses and low density urban vegetation (Fig. 5). To analyze temporal lag effects for these land covers we compared spatial subsets of positive and negative correlations separately. Correlations increase slightly at lags 1 or 2 then return to the no lag level as lags are increased (Fig. 6B). Riparian vegetation is moderately positively and Arizona Upland is negatively correlated with temperature (Figs. 5 and 6B).

### *3.3. Correlations between NDVI spatial patterns and multiscale climate patterns along the urbanization gradient*

Spatial relationships of NDVI with rainfall reveal moderate to marginal positive correlations for the two desert land covers and variable positive-negative correlations for riparian vegetation (Figs. 4 and 7). They all exhibit seasonal dynamics that tend to repeat patterns of growth. Strongest correlations occur during spring and then decline sharply in the Larrea-Ambrosia desert and more gradually in the Arizona Upland (Fig. 7A). NDVI-temperature correlations are negative with absolute temporal patterns mirroring that of NDVI-rainfall correlations (Fig. 7B).

Urban vegetation, croplands, and cultivated grasses show essentially no spatial correlation with both climate variables during any time of year or temporal scale of climate variable (Fig. 7A and B).

While longer time periods (4–5 month rainfall) are generally better (i.e. more temporally consistent) at predicting NDVI patterns of the entire spring and summer seasons, no single temporal scale of rainfall is best across all seasons as demonstrated by single year dynamics of spatial correlations for the two desert vegetation classes (Fig. 8). Correlations with shorter periods of rainfall vary substantially and can surpass the predictive power of longer period rainfall. When all correlations decline in early September following the end of monsoonal precipitation, the 2–4 weeks rainfall often has the highest correlation with NDVI (Fig. 8).

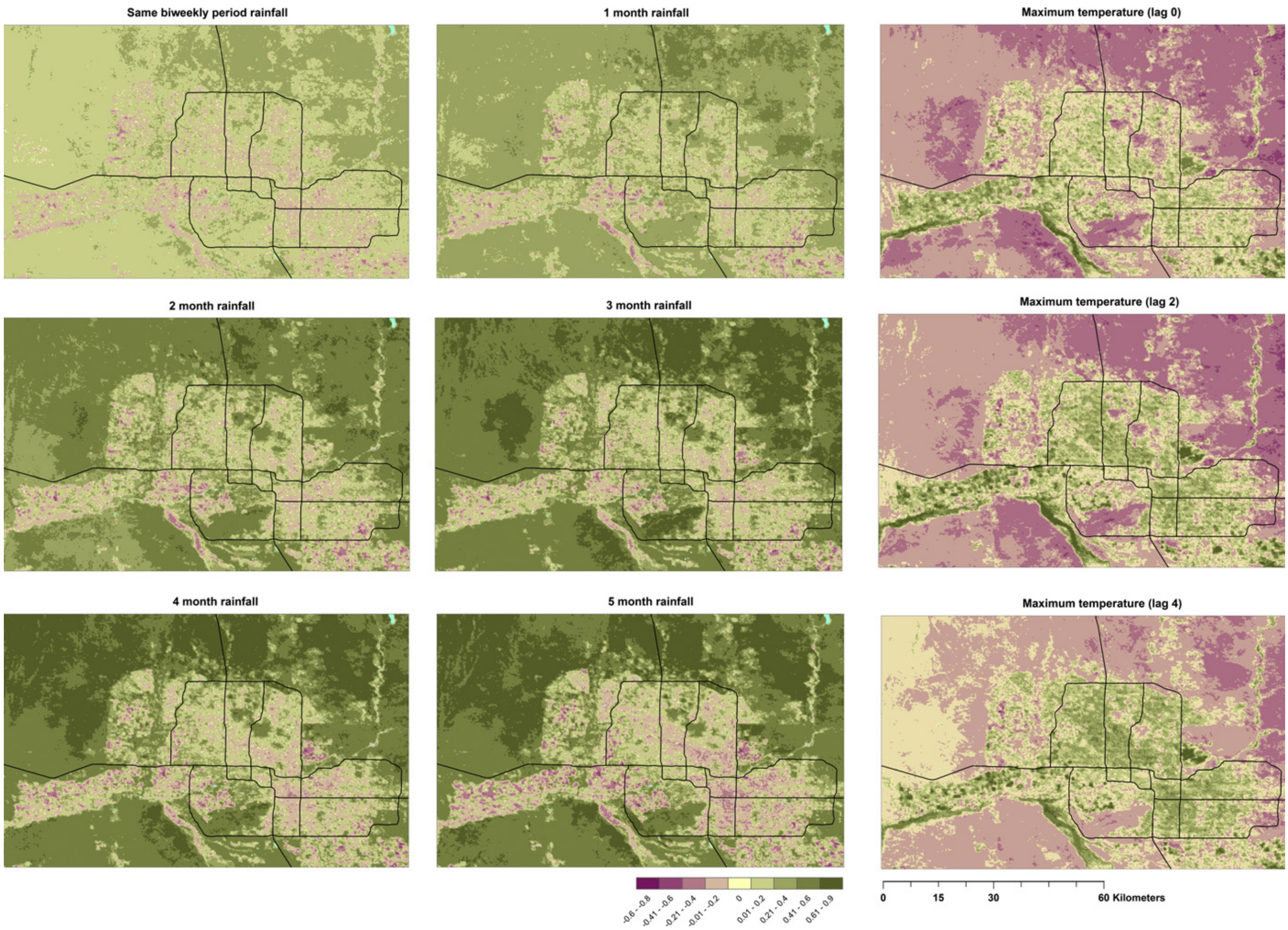


**Fig. 5.** Maps of correlations between NDVI and rainfall aggregated over different time periods and between NDVI and air temperature analyzed at several temporal lags. Rainfall accumulation periods correspond to those in Table 1 as follows: 1 month = 0–2, 2 month = 0–4, 3 month = 0–6, 4 month = 0–8, and 5 month = 0–10.

## 4. Discussion

### *4.1. Patterns of desert vegetation phenologies and phenological transformations introduced by agricultural and urban development*

Our findings suggest several generalizations that describe land surface phenology in Sonoran desert and how land use and land cover changes transform phenological patterns. Desert vegetation was found to have the least number of annual growing seasons. Growth in desert usually starts as rapid emergence of opportunistic species (C4 grasses and summer annuals) triggered by monsoonal precipitation, and ends during the fore-summer drought. It is sufficiently truncated during dry winter-spring conditions. While desert shrubs are also known to respond to summer rain, they seldom attain the size of spring leaves (Beatley, 1974). Peak of greenness in desert communities coincides with maximum growth of shrubs and winter annuals. Conversely, agricultural and urban developments introduce annual growth multimodality. This characterizes intra-annual crop rotation and repeated grass overseeding practices. Active agriculture and cultivated grasses, land uses that strive to meet societal demands for food and recreation, often have more than one growing season a year. Inexpensive water available on an annual basis and warm winters make these practices feasible and profitable. In fact, tourism which relies on resorts with mesic landscaping and golf courses is the second most important industry in the Phoenix metro area (Hartz et al., 2006).

Compared to multimodality, growth length does not display any trend along the urban–rural gradient. Instead, urban land covers are characterized by intermediate length with dense urban vegetation having the second longest growing season. These patterns can be explained by such factors as frequent dominance of urban vegetation by large woody species, some of them evergreen plants, and active maintenance. Winter deciduous riparian ecosystems exhibit the longest growth because of their proximity to water courses and the presence of near-surface water table. Annuals and perennial forbs contribute considerably to primary production of the Larrea-Ambrosia desert (Went, 1949), but they stay productive only for a short period of time (Patten, 1978). On the other hand, Arizona Upland communities tend to exhibit longer growth, sometimes comparable with urban vegetation. Several environmental and ecological factors may account for this, including increased precipitation (Comrie and Glenn, 1998), denser vegetative cover characterized by multi-layered structure, arborescent physiognomy, and higher compositional diversity (Brown, 1994). Temporal differentiation of water use by different functional groups and plant populations is also likely to play a role (Angert et al., 2007). Phenology can further help us elaborate on the temporal niche concept (Pau et al., 2011) by providing a mechanism by which resources are partitioned through time resulting in reduced competition of co-occurring species. Overall, higher functional and species diversity of Arizona Upland communities is likely to allow for more efficient use of water (Huxman et al., 2004).

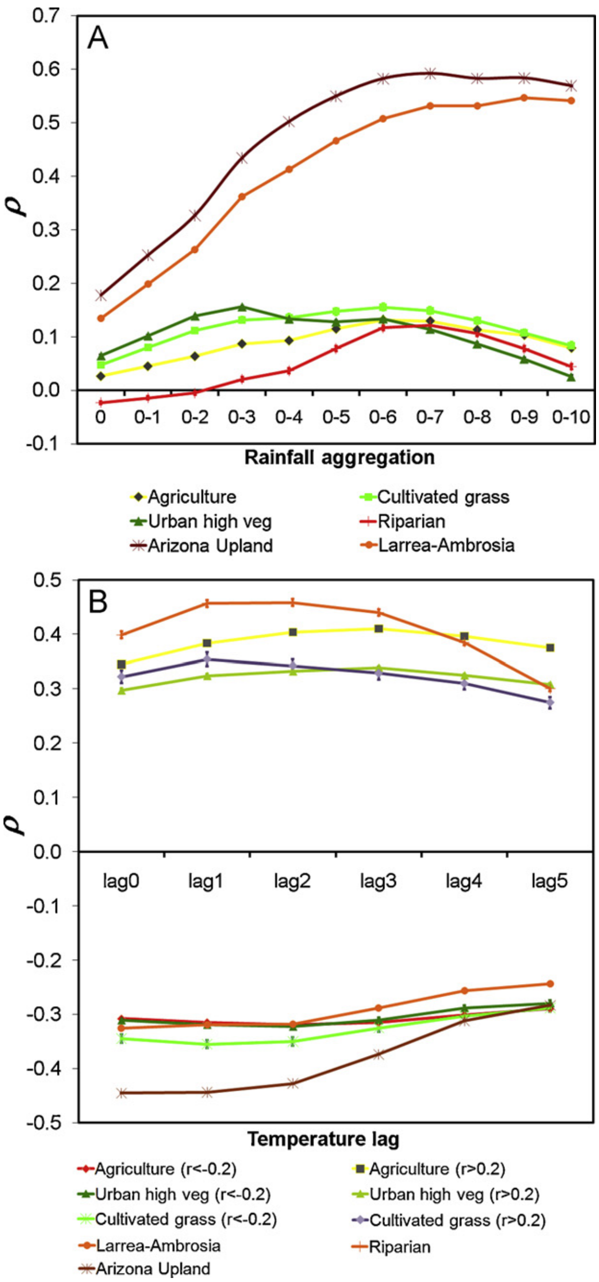


**Fig. 6.** Effects of rainfall accumulation periods and maximum air temperature temporal lags on NDVI-rainfall (A) and NDVI-temperature (B) correlations. The values are spatially averaged correlations stratified by land cover. Numbers on the first *X*-axis indicate aggregation levels (0 = same biweekly period rainfall; 0–1 = rainfall accumulation over the current and the first previous period, 0–2 = current and two previous periods etc.).

The knowledge of differences in phenology is important for understanding patters of primary productivity. For example, recent modeling indicated that net carbon flux in temperate deciduous forest may increase by 2% in response to just a 1-day expansion of growing season (White et al., 1999). Results from the current research support previously investigated patterns of aboveground primary productivity in the study area (Buyantuyev and Wu, 2009). The highest per unit area productivity of riparian ecosystems can be directly related to their high greening rates and long growing season. Agriculture is more productive than all other anthropogenic land covers thanks to a combination of growth multimodality, very fast growth rates, irrigation, and fertilization.

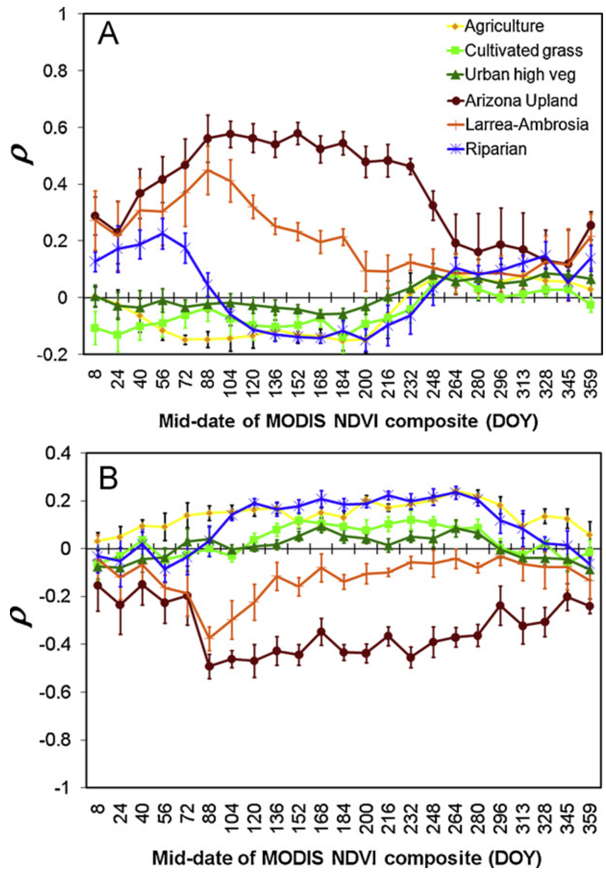


**Fig. 7.** Dynamics of correlation coefficients (5-year mean ± SE) between spatial structure of NDVI and climatic variables: (A) correlations of NDVI with 5-month rainfall; (B) correlations of NDVI with maximum air temperature (lag0).

### *4.2. Differences in responses of vegetation phenology to multiscale climatic triggers along the urbanization gradient*

Our results suggest that land surface phenology in Sonoran desert is primarily regulated by 3–5 month rainfall, whereas temperature does not serve as a trigger, which supports previous findings obtained at fine spatial scales (Bowers and Dimmitt, 1994; Phillips and Comus, 2000). More broadly, our results generally agree with those from other similar studies conducted in semi-arid and arid regions of Africa and grasslands of North America (Davenport and Nicholson, 1993; Justice et al., 1985; Nicholson and Farrar, 1994; Wang et al., 2001). While growth in riparian areas appears to be driven by temperature fluctuations, temperature correlates negatively with desert vegetation growth. Three possible mechanisms were suggested to explain such negative NDVI-temperature correlations including direct inhibition of photosynthesis, cease of growth due to water stress, and covariance between temperature and rainfall, with lower temperatures linked to increased cloudiness during precipitation events (Wang et al., 2003). Temperature and rainfall do not co-vary in our study area, so we believe occasional cloud cover does not affect NDVI-temperature correlations. Physiological explanation of negative NDVI-temperature correlations is deemed as the most plausible one. High temperatures stimulate water loss from the soil and impose water limitations to carbon uptake by local plants (Shen et al., 2008).

Urban and agricultural vegetation growth is clearly decoupled from climatic drivers as suggested by our correlation analyses. We believe two main processes are responsible for this. First, the majority of man-made plant communities in Phoenix are fundamentally

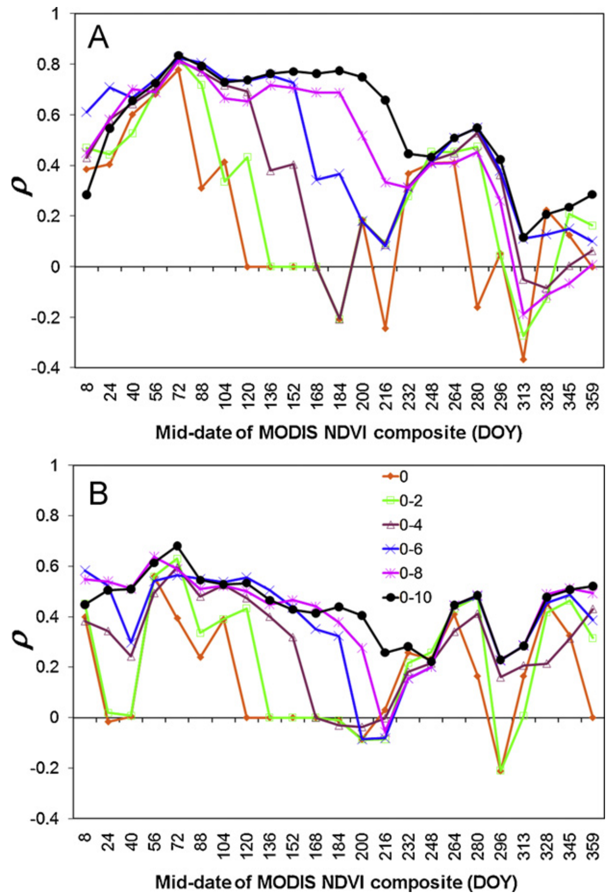


**Fig. 8.** Temporal curves of correlation between spatial structure of NDVI and rainfall accumulated over a range of aggregation levels in 2004 in Arizona upland (A) and Larrea-Ambrosia (B) desert.

different from the outside desert in that they are largely created by humans with specific goals in mind (food production, aesthetics, shading, or recreation). Previous work did not find any generalities in plant species or functional group composition throughout the urbanized area (Gries et al., 2004). Mixed urban communities composed of plants of different evolutionary histories and physiological mechanisms make it difficult to predict phenological patterns at the ecosystem and landscape levels. Additional data on purposes for creating each vegetation patch in the urban area as well as human preferences can help in this issue. Second, designed vegetation is usually heavily managed which reduces irregularity and limited availability of water and nutrients. Additionally, live urban plants can be frequently displaced, such as transported from plant nurseries to sales lots, streets, and yards. It can potentially further complicate remote sensing of urban vegetation, especially at higher spatial resolutions of Landsat or SPOT satellite data.

### *4.3. Differences in predictive ability of vegetation patterns by spatio-temporal climate patterns along the urbanization gradient*

Spatial distribution of managed plant communities is essentially uncorrelated with climate spatial patterns. It is instead expected to be predicted by socio-economic rather than environmental variables. We identify this as a heavily understudied topic that deserves to be included explicitly in the framework of integrated studies of urban ecosystems (Pickett et al., 2011).

Conversely, rainfall spatial patterns can effectively explain spatial variation of desert NDVI, although the relationship varies seasonally. Correlations begin to rise in late autumn when annuals comprising more than 50% of local flora germinate. After the peak in March correlations in the Arizona Upland stay relatively high for most of the growing season indicating spatial agreement of sparse vegetation and small amounts of rain received prior to the fore-summer dry period (May–June). Effects of variable precipitation are most dramatic in the Larrea-Ambrosia desert whose green aspect is formed by annuals and sparse shrubs that both become inconspicuous during droughts. In general, vegetation patterns are more predictable in the winter and spring, which reflects higher dependability of established storm tracks and more consistent winter precipitation.

Riparian ecosystems have the least variable growth patterns due to reliable sources of water drawn from a larger area. They are uncorrelated or negatively correlated with on-site rainfall, but more accurate analysis of their dependency on precipitation requires incorporation of detailed hydrologic routing within watersheds.

As shown previously (Wang et al., 2001), testing multiple temporal lags and accumulation periods for climate variables is helpful in detecting optimal time scales of climate-vegetation coupling. While time lags for precipitation did not affect correlations in our study, we found that systematic accumulation of rainfall up to about 3–5 months always provided a steady rise in correlation. In addition, our results suggest that at different times of year desert vegetation distribution is explained by rainfall of a different magnitude. In particular, autumn NDVI patterns are better explained by short-term and summer NDVI by longer term rainfall (Fig. 8). Overall, our study supports the observation that success of spring primary producers in Sonoran desert is dependent heavily on autumn germination triggered by rain. Moreover, the triggering rains must be followed by sufficient precipitation spread throughout the winter season (Beatley, 1974; Phillips and Comus, 2000).

## 5. Conclusions

Greenspaces have high rates of ecological processes in cities, and also provide a variety of ecosystem services, including mitigating microclimates, improving air quality, sequestering carbon dioxide, and providing food, wildlife habitat, and recreation opportunities. Understanding vegetation dynamics along urban–rural gradients is important for assessing the effects of urbanization on ecological processes and estimating benefits essential for the well-being of urbanites. Urban–rural differences in phenology should reflect changes in three main drivers: ontogenic mechanisms at the genetic and physiological levels, environmental cues of phenology–photoperiod and climate, and land management. Our study shows that urbanization results in a complex pattern of vegetation phenology in a dryland environment. Because of irrigation, agricultural and urban vegetation covers are decoupled from the climatic controls and exhibit multimodal growth patterns. Specifically, NDVI dynamics of urban and agricultural land covers are out of sync with variations of precipitation and temperature in the region. While crop-fields are characterized by the shortest growth length and fastest green-up rates, urban vegetation stays photosynthetically active for significantly longer periods. Both temporal and spatial patterns of native desert vegetation are regulated strongly by 3–5 month accumulated precipitation and negatively correlated with temperature. In contrast, riparian vegetation is uncorrelated with rainfall and positively correlated with temperature.

Overall, urbanization results in a greater diversity of phenological patterns that are beyond the control of biophysical factors of the region. Instead, the dynamics of urban and agricultural vegetation are controlled predominantly by socio-economic drivers such as landscaping and water irrigation patterns. More than likely, these alterations will profoundly affect biodiversity and ecosystem functioning at local and regional scales, and their long-term ecological and environmental consequences are yet to be fully understood. Towards that end, our findings shed new light on the interactions among vegetation growth, climate variability, and urbanization in the arid southwestern United States and dryland landscapes around the world.

## Acknowledgments

We appreciate Nancy Grimm and John Briggs for insightful discussions. David Iwaniec, Darrel Jenerette and William Stefanov provided valuable feedback on an earlier draft. We also thank Lars Eklundh and Per Jönsson for providing TIMESAT software.

The study was supported by the National Science Foundation under Grant No. DEB-0423704, Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER) and under Grant No. BCS-0508002 (Biocomplexity/CNH).

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