Changes in evapotranspiration and phenology as consequences of shrub removal in dry forests of central Argentina

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ABSTRACT

More than half of the dry woodlands (forests and shrublands) of the world are in South America, mainly in Brazil and Argentina, where in the last years intense land use changes have occurred. This study evaluated how the transition from woody-dominated to grass-dominated system affected key ecohydrological variables and biophysical processes over 20 000 ha of dry forest in central Argentina. We used a simplified surface energy balance model together with moderate-resolution imaging spectroradiometer–normalized difference vegetation index data to analyse changes in above primary productivity, phenology, actual evapotranspiration, albedo and land surface temperature for four complete growing seasons (2004–2009). The removal of woody vegetation decreased aboveground primary productivity by 15–21%, with an effect that lasted at least 4 years, shortened the growing season between 1 and 3 months and reduced evapotranspiration by as much as 30%. Albedo and land surface temperature increased significantly after the woody to grassland conversion. Our findings highlight the role of woody vegetation in regulating water dynamics and ecosystem phenology and show how changes in vegetative cover can influence regional climatic change. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS   water dynamics; ecosystem phenology; remote sensing; NDVI; selective deforestation; Dry Chaco

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INTRODUCTION

Temperate dry woodlands (forests and shrublands) constitute a significant proportion of the world's terrestrial ecosystems and play a critical role in climate regulation and the provision of ecosystem goods and services (Reynolds *et al.*, 2007; Leu, 2010; Rotenberg and Yakir, 2010). Many of these dry woodlands have been traditionally used for wood harvest and livestock grazing, and only a small fraction of their original area remains unaltered (Sánchez-Azofeifa *et al.*, 2005). More than half of global dry woodlands occur in South America, mainly in Brazil and Argentina (Miles *et al.*, 2006), where in the last decades intense land use transformations have occurred, mainly from woody-dominated systems to cropland and pastures (Gasparri and Grau, 2009; Guida Johnson and Zuleta, 2013).

Such large-scale conversion of vegetative land cover has the potential to significantly alter a number of key biophysical processes (e.g. albedo and surface roughness) (Zeng and Neelin, 2000; Houspanossian *et al.*, 2013) and ecohydrological processes (e.g. the water balance) (Wilcox and Huang, 2010; Wilcox *et al.*, 2012). Ecosystem water balance is largely determined by differences between precipitation and evapotranspiration (ET) (Eagleson, 1982). Transformations in vegetation cover and composition can influence ET in a variety of ways, including changes in plant transpiration (Allen *et al.*, 1998), plant phenology (Bisigato and Laphitz, 2009), leaf area, rooting depth (Huxman *et al.*, 2005) and carbon balance (Scott *et al.*, 2006). To quantify these dynamics in arid and semi-arid areas requires large-scale observations over time because the spatial distribution of vegetation and resources (water, nutrients, etc.) is not uniform (McCulley *et al.*, 2004; Reynolds *et al.*, 2004). The use of remote sensing by satellite observation remains the best alternative to achieve this goal as it can be used to obtain long-term datasets over large areas characterized by high spatial heterogeneity (Di Bella *et al.*, 2000; Kerr and Ostrovsky, 2003). One common approach to estimate ET by remote sensing is to combine land surface temperature (LST) and vegetation spectral indices, such as the normalized difference vegetation index (NDVI) (Roerink *et al.*, 2000; Su, 2002). Moreover, because of the high

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correlation between vegetation spectral indices and photosynthetic active radiation, spectral indices can be used to estimate aboveground net primary productivity (ANPP) (Monteith, 1972; Paruelo *et al.*, 2001). In turn, the NDVI–ANPP relationship can be used to evaluate ecosystem growth phases and to explore the impact of disturbances on plant phenology at large spatial scales. Although certain aspects of phenology, such as fruiting or differential senescence, cannot be evaluated using remote sensing, it is possible to observe the timing and length of the growing season, which are useful parameters to elucidate the contributions of specific plant functional types (e.g. grasses, trees and shrubs) to carbon and water dynamics (Cleland *et al.*, 2007).

Wilcox *et al.* (2012) concluded that there are many gaps in our knowledge about the biophysical and ecological consequences of woodland to grass transitions. The objective of this study was to examine some of these gaps: specifically, how large-scale transitions from woody-dominated to grass-dominated systems in the Dry Woodlands of central Argentina affect key biophysical (albedo and surface temperature), carbon (ANPP) and ecohydrological (ET) processes. We used remote sensing and meteorological data to estimate changes in ET, LST, albedo, ANPP and vegetation dynamics over large areas of dry woodlands that were deforested and converted to grasslands for four complete growing seasons, during the period from 2004 to 2009.

METHODS

Study area

Field work was performed at the San Luis Province, west-central Argentina (33.5°S; 66.5°W) (Figure 1). The study area covered ca. 200 km² in a transitional area between the Chaco Dry Forests and the Monte scrublands (Morello, 1955). Overstory is dominated by two tree species: *Prosopis flexuosa* and *Aspidosperma quebracho-blanco*. Understory consists of shrubs such as *Larrea divaricata* and *Lycium chilense* and perennial C_3 grasses such as *Aristida mendocina* and *Pappophorum* spp. Rainfall occurs mainly from November (Southern Hemisphere spring) to March (autumn). Mean annual rainfall is 400 mm, with 60% of all events ≥20 mm and 7% by events <5 mm (Magliano *et al.*, 2014). Air temperature ranges from 30 °C in summer to 5 °C in winter. Meteorological data were obtained from a weather station located in the centre of the study area. Soils are alluvial and calcareous material, with gentle slopes (<2%). Because of the high spatial heterogeneity, soil organic matter varies between 1% and 2.5% (Peña Zubiate *et al.*, 1998).

Experimental design

We selected 15 plots (ranging in size from 60 to 300 ha) that were cleared (disturbed) in different years: four in 2005, six in 2006 and five in 2008. Clearance was done by a roller-chopping technique that targets shrubs and small trees, leaving larger trees undisturbed (approximately 5–20 trees ha⁻¹). As controls, we selected eight adjacent, undisturbed plots based on their proximity to the disturbed plots (all within a maximum distance of 200 m). The distance between the weather station and the study plots varied from 1 to 7 km depending on the plot. There were no differences in soil texture and bulk density between the disturbed and undisturbed plots (Marchesini *et al.*, 2013).

Remote sensing data

Two sets of satellite data were used based on the moderate-resolution imaging spectroradiometer (MODIS)/TERRA
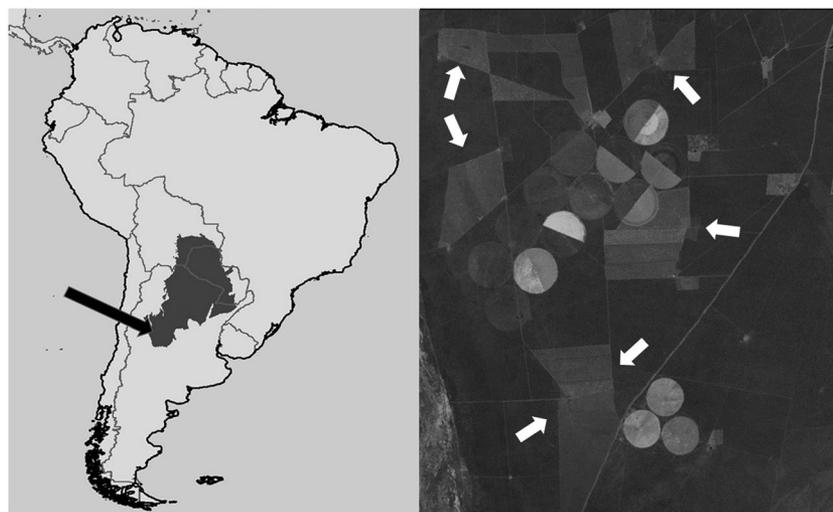

Figure 1. Study area indicated by the black arrow on the left picture, and the shaded area represents the South American Chaco. White arrows on the right indicate woodland areas that were replaced by grassland. Circles are sites cleared for agriculture.

and TM LANDSAT 5 platforms. The MODIS product included a series of 23 images per year (one every 16 days) from January 2004 to December 2009 from the MODQ13 (NDVI) with a resolution of $250 \, m^2$. All images were atmospherically corrected and masked for water, clouds, aerosols and cloud shadow. LANDSAT images were geometrically and atmospherically corrected following Chander *et al.* (2007). A total of 24 LANDSAT images (scene 230/83) were processed, with a spatial and temporal resolution of $120 \, m^2$. Each annual series contained one image corresponding to each season. Images were obtained from the United States Geological Survey website.

Vegetation dynamics

Changes in ecosystem phenology were characterized using NDVI. Time series of MODIS images from 2004 to 2009 were processed using TIMESAT software (Jönsson and Eklundh, 2004). TIMESAT processed time series data by considering 23 images per year. The maximum, minimum and peak values of NDVI and the start, end and length of the growing season (by growing season, we refer to the period of actual vegetation growth, rather than that over which vegetation can potentially grow) – before and after disturbance – were calculated using a filtering function (Savitzky–Golay) to suppress extreme values. The beginning (and end) of the growing season was calculated as the time for which the left (or right) edge of the curve had increased (or decreased) to a level defined following Jobbágy *et al.* (2002).

Albedo and land surface temperature

Land surface temperature was determined using the single channel method (Jiménez-Muñoz *et al.*, 2009) from the LANDSAT thermal infrared channel (TM6). This method requires water vapour and emissivity (ε) values. Water vapour was obtained from the MODIS product MOD07 while ε was calculated according to Sobrino *et al.* (2008). Surface albedo was calculated according to Liang (2000) using the combination of bands 1, 3, 4, 5 and 7 of LANDSAT 5 TM. All images were corrected in order to convert top atmospheric radiances to directional radiance.

Actual evapotranspiration

Evapotranspiration was estimated using the simplified surface energy balance model (S-SEBI) (Roerink *et al.*, 2000), which is based on an energy balance equation that combines reflectance and LST under extreme dry and wet conditions. Daily actual ET (ET_d, mm) was estimated as

$$ET_d = \frac{\Lambda_i R_{ni} C_{di}}{L} \qquad (1)$$

where Λ_i is the fraction of evaporation estimated from the relationship between LST and surface albedo (Roerink *et al.*, 2000). The term R_{ni} is the instantaneous net

radiation, C_{di} is the ratio of the daily net radiation to R_{ni} (set to 0.30 following Seguin and Itier (1983)) and L is the latent heat of vaporization. Net radiation was estimated from Hurtado and Sobrino (2000). The estimation error of ET by this method is $< \pm 1 \, mm \, day^{-1}$ (Roerink *et al.*, 2000).

To provide a check for our ET estimations using S-SEBI, we compared them with ET as obtained by the conventional Blaney–Criddle method (1950). We used air temperatures from a local weather station located in an undisturbed plot and a dry forest coefficient ($Ks = 0.6$) (Allen *et al.*, 2006). We do not imply this validation method as exact, because it is based on standard atmospheric conditions, but still provided an independent standard to compare the magnitude and trends of ET.

Data analyses

Normalized difference vegetation index, albedo, actual ET and variables related to ecosystem phenology (start, end and length of the growing season) were compared between disturbed and undisturbed plots using a repeated measures analysis of variance (Littell *et al.*, 1996). The value of each variable for each date was the average value of all pixels for each plot; thus, the sampling unit for each treatment was the plot, not the pixel. In all cases, we used a significance level of $P < 0.05$.

RESULTS

Vegetation dynamics

With respect to control plots, NDVI declined by 15 to 21% after shrub removal. No differences between plots were detected before disturbance, except for those areas that were about to be cleared in 2006 (Table I). The lower NDVI in the disturbed plots persisted during the three following growing seasons. The length of the growing season was strongly shortened after shrub elimination. The differences in growing season length between disturbed and control plots varied from 18 days to 3 months, depending on the time elapsed since disturbance (Table I). This was the result of two interacting effects: a delay in the beginning of the growing season (spring–summer) and an earlier end in the autumn. No significant differences in the length of the growing season were found between undisturbed and disturbed prior to the disturbance (Table I).

Following disturbance, as successional regeneration proceeded, differences in the length of the growing season between the disturbed and undisturbed areas became less pronounced. Three years after disturbance, there was no difference in the growing season length between the undisturbed and disturbed areas (Table I). However, NDVI still remained lower in the disturbed areas (~15% lower), showing that NDVI required at least 4 years to recover to its original values in the cleared areas.

Table I. Average values and standard deviation per site (columns) for moderate-resolution imaging spectroradiometer–normalized difference vegetation index (NDVI) integral, length, start and end of the growing season, for undisturbed and disturbed sites in different years (rows). Start and end correspond to Southern Hemisphere spring–summer and autumn–winter months respectively. Standard deviation for start and the end of the growing season is given in days. Asterisk indicates significant differences between disturbed and undisturbed sites for the same year (within-rows comparisons, $P < 0.001$). Bold data indicate the year in which the plot was cleared.

	Undisturbed ($N=8$)	Disturbed 2005 ($N=4$)	Disturbed 2006 ($N=6$)	Disturbed 2008 ($N=5$)
2005–2006				
NDVI integral	0.53 (±0.02)	**0.42 (±0.01)***	0.47 (±0.04)*	0.53 (±0.02)
Length	280 (±5)	**193 (±33)***	263 (±58)	284 (±8)
Start	19 October (±3)	**25 December (±30)***	13 November (±37)*	17 October (±5)
End	26 July (±2)	**06 July (±5)***	03 August (±25)	27 July (±5)
2006–2007				
NDVI integral	0.53 (±0.02)	**0.47 (±0.02)***	0.44 (±0.02)*	0.53 (±0.01)
Length	263 (±10)	**229 (±16)***	190 (±16)*	259 (±16)
Start	27 October (±4)	**03 November (±4)**	04 December (±15)*	30 October (±10)
End	17 July (±8)	**20 June (±15)***	12 June (±9)*	16 July (±10)
2007–2008				
NDVI integral	0.52 (±0.02)	**0.46 (±0.02)***	0.44 (±0.02)*	0.48 (±0.02)*
Length	268 (±4)	**208 (±29)***	188 (±40)*	278 (±17)
Start	11 October (±5)	**29 November (±28)***	11 December (±36)*	11 October (±5)
End	05 July (±5)	**24 June (±4)***	15 June (±13)*	15 July (±17)**
2008–2009				
NDVI integral	0.48 (±0.02)	**0.41 (±0.02)***	0.40 (±0.02)*	**0.41 (±0.01)***
Length	307 (±8)	**289 (±20)***	289 (±18)	**230 (±12)***
Start	29 September (±6)	**04 October (±8)**	03 October (±9)	**14 November (±12)***
End	02 August (±6)	**20 July (±19)**	19 July (±11)*	**02 July (±5)***

In undisturbed plots, the growing season started during the early spring (September–October) and continued until late autumn (May–June), but in some years it was extended up to the beginning of winter (July). The lowest NDVI values were recorded before rains (late September) while the highest values were registered during January and February, coinciding with the rainy season. A longer-term series showed that, on average, the total growing season in undisturbed areas covered a period of 277 days, with an annual variation coefficient of about 6%.

Land surface temperature and albedo

Before vegetation removal, LST and albedo were similar between plots for all dates and regardless the season (Figure 2). After disturbance (showed in the figure by an arrow), LST was on average of 1 to 4 °C higher in disturbed areas compared with undisturbed ones (Figure 2). Similar to LST, albedo increased significantly following disturbance; differences between plots were less than 5% prior to disturbance and up to >60% afterwards (Figure 2). Average albedo values were 0.08 and 0.12 for undisturbed and disturbed plots respectively.

Evapotranspiration dynamics

Vegetation removal reduced ET by 30% (Figure 3, grey bars). Changes in ET varied from 0.5 to 3 mm day^{-1}

depending on the date. Disturbed and undisturbed areas showed seasonal differences in daily ET: summer values (January–February) ranged from 4.0 to 8.0 mm day^{-1} while winter ones varied from 3.0 to 6.0 mm day^{-1} for disturbed and undisturbed areas respectively. The regression obtained from S-SEBI for undisturbed plots versus those values obtained through the Blaney–Criddle method were positively related, with a slope close to 1:1 (r^2 0.6, $P < 0.05$) (Figure 5, supplementary information)

Shrub removal also resulted in a higher spatial variability for ET. On average, the spatial coefficient of variation (ET values between pixels of the same plot) for undisturbed areas was less than 9% while in disturbed areas it exceeded 20% (cf. error bars in Figure 3). Figure 4 shows ET spatial distribution for all plots in the study site for two dates, prior and after shrub removal: in 2004, before clearing, all areas (except those circles completely cleared for crops) showed similar ET values (~6 mm day^{-1}) while after clearing a strong contrast between disturbed (red-coloured plots, 3 mm day^{-1}) and their adjacent undisturbed plots (blue-coloured plots, 6 mm day^{-1}) was observed.

DISCUSSION

Our findings show that woodland to grass transitions in dry forests of central Argentina is having a large impact on ecosystem ET via changes in vegetation structure and
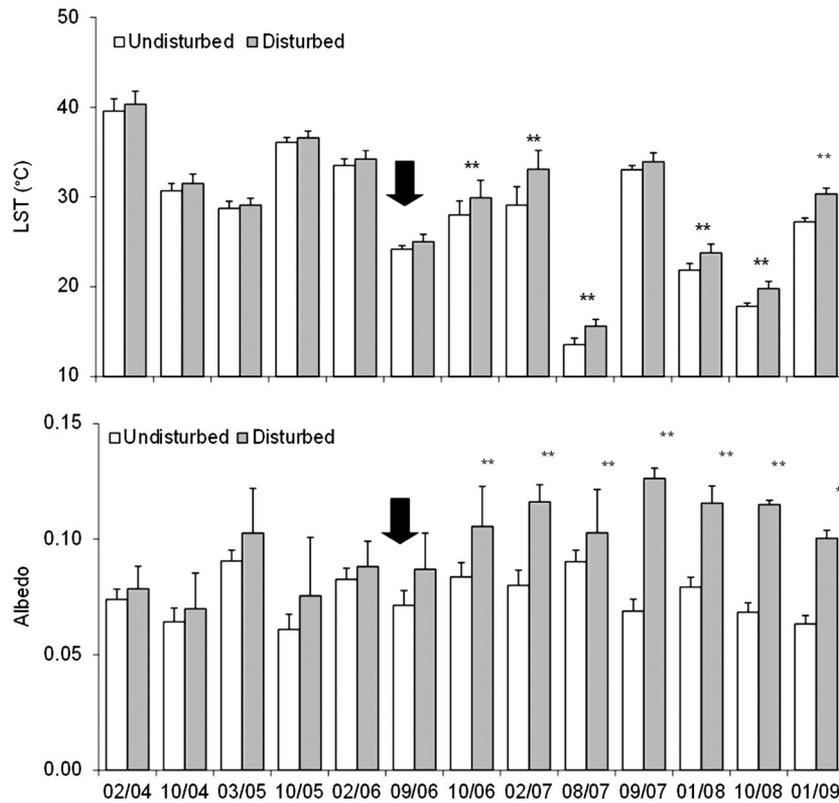
Figure 2. Average values and standard errors for land surface temperature (LST) and albedo from LANDSAT images, for disturbed plots in 2006 and their contiguous undisturbed pairs ($n = 4$ and $n = 6$ for LST and albedo respectively). Data are shown before and after clearing to highlight the effect of vegetation removal on LST. Black arrow indicates the date of woody vegetation removal. Date is indicated as month/year. Asterisks indicate significant differences between treatments at $P < 0.001$.
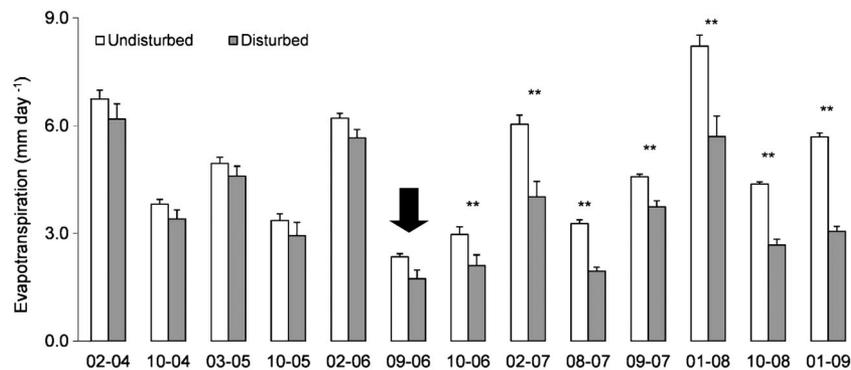

Figure 3. Average values and standard errors for evapotranspiration (mm day^{-1}) estimated from LANDSAT images for disturbed areas cleared in 2006 ($n = 5$) and their contiguous undisturbed plots ($n = 7$). Data are shown before and after clearing to highlight the effect of vegetation removal on evapotranspiration. The black arrow indicates time of woody vegetation removal. Date is indicated by month/year. Asterisks show significant disturbance effect at $P < 0.001$.

phenology. This study revealed that elimination of woody vegetation over large areas of native dry forests shortened the growing season by up to 3 months and modified the water balance via a large reduction in ET.

In contrast to those studies at higher latitudes showing that deforestation, by increasing local temperatures, could promote an extension of the growing season (Cleland *et al.*,

2007; Körner and Basler, 2010), the removal of most woody vegetation in native dry forests in central Argentina shortened the growing season. Most of the woody species removed have evergreen foliage during the unfavourable season (Morello, 1955), which could explain why deforested areas showed a shorter growing season compared with undisturbed forests. Our results confirm
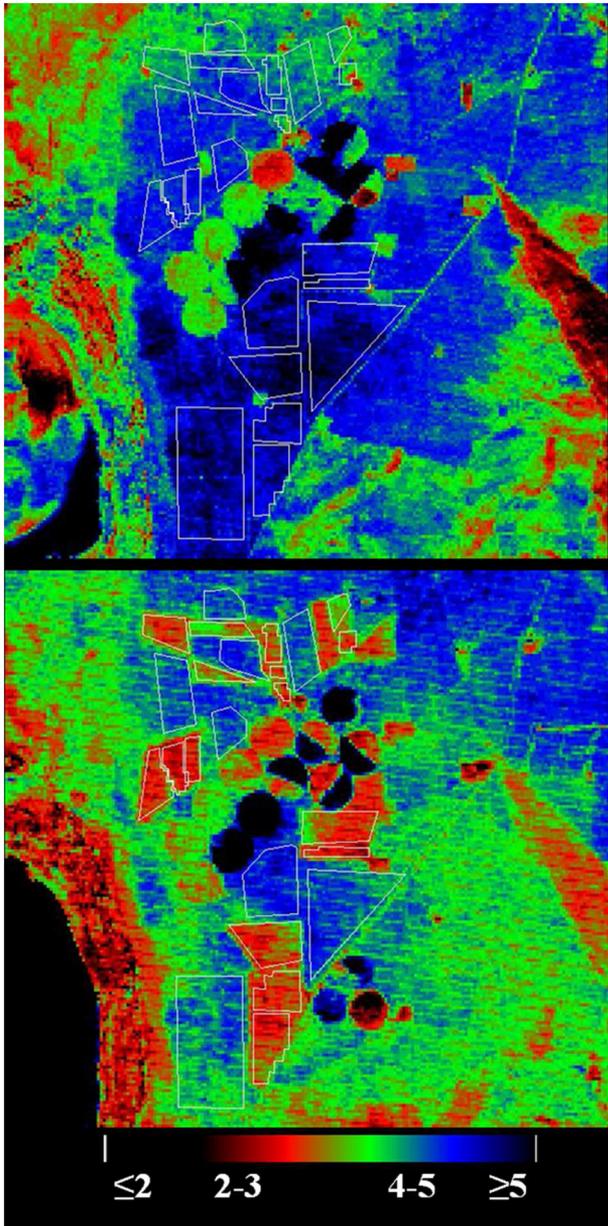
Figure 4. Evapotranspiration (mm day^{-1}) estimated with LANDSAT images for two dates: before shrub removal in February 2004 (above) and after shrub removal, January 2009 (below). Black circles are sites cleared for agriculture. In the image of 2009, red polygons mark areas where shrubs and trees were removed, while blue polygons mark undisturbed forest areas.

previous findings such as those of Koltunov *et al.* (2009) who, using LANDSAT images, showed that selective logging in forests in Brazil changed ecosystem phenology by promoting drying and constraining the green up during the dry season. On the other hand, our results seem opposite to that observed by Wilcox *et al.* (2012) in arid areas of North America, where the invasion of shrublands by grassland increased ET because of the earlier use of water by grasses during spring, when woody vegetation is still inactive.

Although grass biomass increased almost fivefold after disturbance (Marchesini *et al.*, 2009) and the length of the growing season recovered 3 years after clearing, we found that NDVI, a surrogate of ANPP, did not recover. A plausible explanation for why ANPP recovered so slowly after clearing could be the exclusion of key species such as *Prosopis flexuosa*, one of the few nitrogen fixers with deep root distribution. Removal of certain functional types could affect complementary and positive interactions between species. Although this study did not evaluate such interactions, many others have shown that ANNP can increase with species richness, especially with functional group richness (Tilman *et al.*, 1997; Flombaum and Sala, 2008).

The transition from a woody-dominated to a grassland-dominated system produced a sizeable increase in LST and albedo, a pattern that is similar to that observed in tropical and subtropical areas (Gao *et al.*, 2005). For semi-arid regions, it has been proposed that raises in local albedo can decrease convection processes (due to a lower radiation input) and both higher albedo and lower ET can eventually reduce local precipitation (Dirmeyer and Shukla, 1994). Moreover, selective deforestation seems to have a strong impact on sensible heat flux versus that of latent heat: biomass reduction could explain the increase in LST despite the reduction of energy input caused by the increased albedo (Lee *et al.*, 2011). Houspanossian *et al.* (2013) also found an increased albedo (50%) and LST (2.5 °C) in crop areas previously occupied by dry forests in central Argentina.

Evapotranspiration values obtained in disturbed areas were similar to those estimated by Kelliher *et al.* (1993) for global grasslands. Our results also agree with Miao *et al.* (2009) for pastures in plains of Inner Mongolia. Higher values of ET for the forest sites are explained by considering the physical characteristics of the dry forest canopy promoting large water losses. Air turbulence, one of the variables that most strongly influences ET, is usually higher in tall-canopy systems with higher roughness, which favours a strong coupling between atmospheric water demand and transpiration, i.e. the water supply from vegetation. In contrast, in grasslands, where the canopy is less uniform, there is a minor coupling because ET is more strongly driven by net radiation (Nosetto *et al.*, 2005). Our results, however, contrast with Wilcox *et al.* (2012) who concluded that for warm arid areas the invasion or the replacement of shrubs by grasses has minor effects on transpiration since vegetation cover increase after the grass invasion and, consequently, runoff and soil evaporation are reduced.

The replacement of forests by grassland and the severe reduction of ET can impact on other components of the water balance. Santoni *et al.* (2010) showed that the replacement of dry forests by crops in central Argentina

increased deep drainage by 30% and ground water recharges up to $120\,mm\,year^{-1}$. Similar results were obtained by Jayawickreme *et al.* (2011) in agricultural plots in the same area, for which soil profiles revealed a 50% higher soil water storage than in their forest controls. These studies, together with our results here, alert about the potential risk of dryland salinity at regional scales due to the abrupt changes on the groundwater levels (George *et al.*, 1997; Lambers, 2003). On the contrary, runoff seems not to be affected or even decreased after roller-chopped clearing (Aguilera *et al.*, 2003).

Woody vegetation in dry forests of central Argentina plays an important role in regulating climatic variables, especially via their influence on ET. The changes we and others have observed in LST and albedo may also have a major impact on local climate by increasing the proportion of long-wave radiation that is emitted by the surface and retained by the atmosphere (Lee, 2010). In a recent analysis on ecohydrology of ecosystem transitions, Viglizzo *et al.* (2014) suggest that not only anthropogenic but also biophysical factors could play a critical role in determining vegetation changes. They proposed that the hydrological context more than any other variable is what defines the propensity of transitions after a human disturbance, being higher, less resilient and more permanent in arid and semi-arid areas.

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