Vegetation composition and structure changes following roller-chopping deforestation in Central Argentina woodlands

Steinaker Diego F.[1,2], Jobbágy Esteban G. [3], Martini Juan P. [2]Arroyo Daniel N. [2] & Pacheco Jorge L[2]. Marchesini Victoria A. [3,4]

[1] Department of Biology, University of Regina, Regina SK, Canada S4S 0A2.

[2] Instituto Nacional de Tecnología Agropecuaria, Casilla de Correo 17, Villa Mercedes, San Luis, 5730, Argentina.

[3] Grupo de Estudios Ambientales, IMASL – CONICET- Universidad Nacional de San Luis, Ejército de los Andes 950, San Luis, 5700, Argentina

[4] School of Plant Biology. The University of Western Australia 35 Stirling Highway Crawley, WA, 6009, Australia.

Corresponding author: victoriamarchesini@gmail.com

ABSTRACT

Driven by the pressure of increasing forage production for cattle, dry forests and woodlands of Argentina are suffering one of the highest deforestation rates in the world. In this study we combined field work and a remote sensing approach to assess the successional trajectory in terms of functional group diversity and ecosystem phenology, following roller chopping deforestation in a woodland of central Argentina. The first year after disturbance, shrub cover decreased at the same proportion than grass cover increased while tree cover was drastically reduced. After 3 years, shrubs recovered 70% of the original cover and grasses maintained a relatively high proportion, but tree cover remained low. Roller-chopping favoured early over late successional species in the case of woody plants, but had the inverse effect in the case of grasses. At ecosystem scale the length of the growing season was drastically shortened by 100 days following disturbance. Roller chopping improves ecosystem services of provision by enhancing forage's offer but at the same time deteriorated the system by reducing functional plant diversity and by shortening the growing season, with potential cascade-consequences on other ecosystem processes such as the carbon and water dynamics.

Keywords: Argentina woodlands, ecosystem phenology, functional group diversity, NDVI, roller- chopping.

1. INTRODUCTION

In central Argentina, like in many semiarid regions around the world, deforestation is advancing in order to increase forage production and accessibility to cattle (Gasparri et al., 2013; Rueda et al., 2013; Bestelmeyer, 2014). Argentinean dry Chaco is the largest remaining continuous dry forest unit in the continent (Eva et al., 2004) and one of the fastest expanding agriculture frontiers of the world (Zak et al., 2008; FAO, 2010).

The ecological succession after deforestation has been object of extensive literature (Noble and Slatyer, 1980; Guariguata and Ostertag, 2001; Staus et al., 2002; Lohbeck et al., 2012; Lohbeck et al., 2014a; Lohbeck et al., 2014b). Classical studies have shown that this disturbance usually follows a succession with a first occurrence of shade intolerant and annual species followed by shade tolerant, perennials and endemic species (White, 1979; Connell and Slatyer, 1977; Dorrough and Scroggie, 2008). These changes are generally accompanied by other changes in ecosystem functioning. For example, a reduction in functional group diversity could affect primary production and ecosystem phenology with significant-cascade effects at all trophic levels (Tilman, 1997; Clark and McLachlan, 2003; Leniére and Houle, 2009). Additionally, changes in the length of the growing season could eventually affect the carbon cycle and water balance (Körner and Basler, 2010).

Trees and shrubs represent the biomass-dominant plant life form in dry forests and woodlands. Traditionally, climatic conditions have restricted the use of these semiarid areas of central Argentina to extensive grazing and selective logging. In the last decades, however, increments in regional precipitation along with livestock expansion and new technologies have intensified land use in these areas (Oesterheld, 2005; Viglizzo et al., 2010) promoting the reduction of shrubby vegetation and the consequent increment on grass production (Rueda et al., 2013). Like in other dry woodlands around the world, shrub cover is reduced by using "roller choppers", heavy cylinders equipped with transversal blades and moved by bulldozers that chop and crush small- and medium-size woody vegetation. This practice promotes grass production and facilitates cattle foraging (Kunst et al., 2012). However, some woody species in our study area have re-sprout capabilities and they readily initiate new growth from their base (Villagra et al., 2004; Fernández and Maseda, 2006). Although thousands of hectares of dry forests are cleared every year in the Chaco's region (Boletta et al., 2006; Hoyos et al., 2013), few studies have analysed the impact of this disturbance on vegetation composition, phenology and primary productivity.

In this study we assess the successional trajectory, in terms of species and functional group composition, and its associated phenological shifts, in response to roller-chopping deforestation in a woodland area of central Argentina. We selected contiguous deforested sites, which vary on the elapsed time from disturbed (1, 2 and 3 years after rolled-chopping), and adjacent undisturbed sites, to assess impacts on vegetation composition, productivity and phenology; combining *in situ* and remote sensing observations.

2. METHODS

2.1 Study area

Field work was performed in San Luis province, on the west-central region of Argentina (33.5° S 66.49° W, 420 m.a.s.l.). Vegetation is a xerophytic woodland of shrubs and emergent trees (*Prosopis flexuosa*), with a discontinuous gramineous understory layer. Dominant woody species includes the genera *Larrea, Prosopis, Condalia, Lycium and Senna*. Common grass genera are *Pappophorum, Trichloris, Setaria, Aristida, Chloris,* and *Neobouteloua* and represent the main forage resource in the area (Morello, 1955; Morello, 1958). Growing season generally extends from September to April for woody species and from November to March for grasses. Growing season matches the seasonal precipitation distribution. Precipitation is 400 mm per year and usually occurs in events exceeding 20 mm (Salinas del Bebedero, Weather Station). Mean annual temperature is 24° C. Soil has been classified as regosol with a low content of organic matter and sandy-loam texture (Kirby et al., 2001).

2.2 Experimental design

The study was based on the existence of areas that were subject to roller chopping (disturbed areas) and adjacent “untreated” woodlands (undisturbed areas). Roller chopping deforestation was performed by using a cylindrical 18 T roller or drum, 4 m in length and 1.8 m in diameter, pulled by a bulldozer. The roller was equipped with 20 cm high blades running parallel to the axis and spaced 50 cm apart around the cylinder surface. *In situ*, field measurements were performed in March 2007 on contiguous large forest extensions that were roller-chopped in August-December 2004 (29 ha), 2005 (132 ha), and 2006 (91 ha), and on their adjacent undisturbed-control sites (<100 m from them, and >100 ha of extension). On each one of these large rolled-chopped and undisturbed sites we set 3 permanent experimental transects to measure changes in plant life forms and ecological strategies. Thus, there were 3 replicates per each roller- chopped treatment and 3 control-undisturbed sites transects. Until deforestation began, the area was covered by natural woodlands and experienced the same land use history with no intense grazing, logging or fire activity over the last decades. No differences were found between soil texture (*n=3 boreholes per site, F= 2.79, site x depth P=0.12*) and bulk density (*n=2 boreholes per site, F= 1.15, site x depth P=0.37*) between treatment and control sites.

2.3 Plant life forms and ecological strategies

We measured plant species cover (%) by using the line intercept method (Canfield, 1941), on three-100-m linear transects randomly located in each disturbed and control site. Percentage of bare soil and litter was also estimated from each interception line. Each species was later categorized by life forms (trees, shrubs, grasses and forbs) and plant ecological strategies (early and late successional). Plant ecological strategies were defined considering shade tolerance, growth rate, number and size of seeds and seed dispersion strategies (Steinaker *pers. communication*).

2.4 Dynamics of NDVI and ecosystem phenology

We evaluated ecosystem seasonality and changes in phenology by analysing the dynamics of the Normalized Difference Vegetation Index (NDVI) in undisturbed and disturbed areas, throughout eight growing seasons (2001-2009). We used MODIS-TERRA images with 6.2 ha and 16 days of spatial and temporal resolution respectively. The sites for assessing NDVI dynamics were selected considering two criteria: a) They had to be located in the same areas that the experimental transects and b) they had to cover a minimum of four pure MODIS pixels. Both criteria were met since all roller-chopped sites were larger than the required extension. Ecosystem seasonality was characterized by the start, end and length of growing season, and the moment of maximum NDVI “greenness”. We also measured the inter-annual stability of NDVI by using the temporal coefficient of variation (CVt = (standard deviation/mean)*100). All the analyses were performed by using TIMESAT software (Jönsson and Eklundh, 2004) which process time series data by considering 23 images per year. Maximum, minimum and peak values of NDVI and the start, end and the length of the growing season before and after disturbance were calculated using a filtering function (Savitzky-Golay) that suppress extreme values produced by extraordinary events. Starting from the NDVI integral curve as 100%, the beginning or the end of the growing season is then calculated as the time for which the left/right edge of the curve has increased to a user defined level. NDVI thresholds for the beginning and the end of the growing season were defined following Jobbágy et al. (2002).

2.5 Statistical Analysis

As measurements were conducted on the same experimental unit over time, we used the PROC-MIXED repeated measurement analysis to compare NDVI dynamics of each treatment over time. For texture and bulk density we performed a repeated measurement analysis considering depth as a repeated measure and using the same procedure. Comparisons of plant cover (%) among different sites (disturbed and undisturbed sites) were performed using a one-way ANOVA. All analyses were completed using SAS version 6.12 (SAS Institute, Cary, North Carolina, USA).

3. RESULTS

Plant life-form considerably changed after roller-chopping, mainly from woody to herbaceous vegetation. The first year after disturbance, shrub cover decreased almost at the same proportion (3:1) than grass cover increased (shrubs from 80 to 26% and grasses from 24 to 87%, Fig. 1). However, after 3 years, shrubs recovered 70% of their initial cover while grasses maintained a relatively high cover (74%, Fig. 1). Trees were the most affected group with their cover being reduced from the 20% to 2% in the first year and no recovery found afterwards. Forbs showed a variable pattern, without significant differences between undisturbed and disturbed areas (Fig. 1). Litter cover raised from 60 to 75% and the bare soil area was reduced from 34 to 16%.

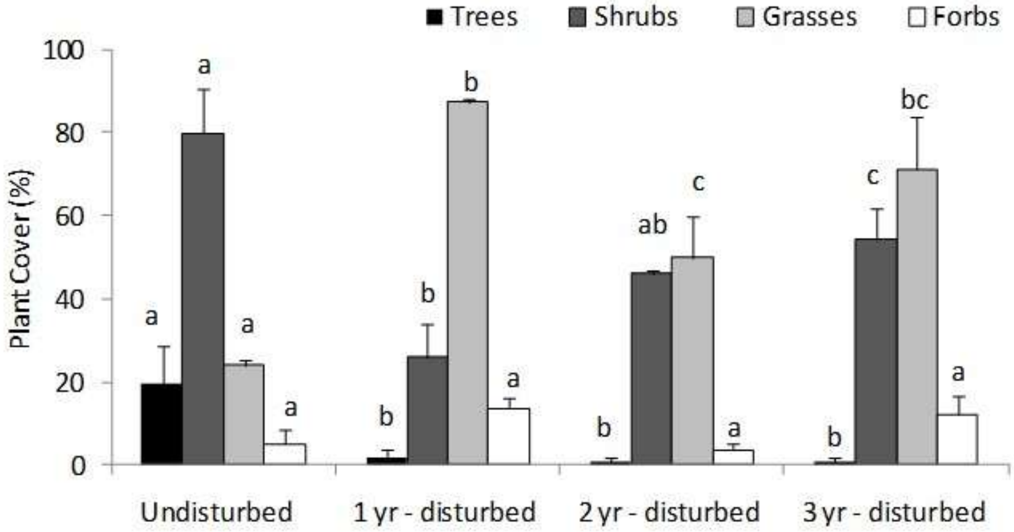

Figure 1. Tree, shrub, grass and forbs cover (%) in undisturbed and disturbed woodland areas of 1, 2 and 3 years old. Bars show mean values and standard errors. Letters compare undisturbed and disturbed areas within each plant life-form (Dunkan 's post-hoc test, $P<0.05$).

3.1 Plant ecological strategies

Roller-chopping changed plant ecological strategies within plant life-forms, from late to early successional species in woody species, but conversely in grasses (Table 1). Although all woody species (shrubs and trees) were affected, early succesional shrubs such as *Larrea divaricata*, *Lycium chilense* and *Senna aphylla* recovered from the disturbance, but late successional *Condalia microphilla* and *Prosopis flexuosa* do not (Table 1). On the other hand, early successional grasses *Aristida mendocina, Sporobolus pyramidatus* and *Gounia paraguayensis* tended to diminish after roller chopping, but late successional *Setaria leucopila, Digitaria californica* and *Trichloris crinita* significantly increased their cover (Table 1).

Table 1: Mean plant cover (%) of dominant grass and woody species in undisturbed forest and 1, 2 and 3 year disturbed areas. LS: late successional species, ES: early successional species. Letters compare undisturbed and deforested areas within each species (Dunkan 's post-hoc test, $P<0.05$).

Species/sites	Undisturbed Forest	Deforested area (1 yr)	Deforested area (2 yr)	Deforested area (3 yr)	Change direction
Trees					
Prosopis flexuosa (LS)	19.8 a	0.0 b	0.3 b	0.3 b	↓
Shrubs					
Condalia microphilla (LS)	7.7	2.7	5.3	2.0	↓
Lycium chilense (ES)	11.2	11.0	9.7	18.0	↑
Senna aphylla (ES)	2.2	1.5	4.8	1.7	↑
Larrea divaricata (ES)	50.0 a	8.5 b	22.6 ab	28.7 ab	↑
Grasses					
Setaria leucopila (LS)	16.3 a	27.5 a	29.3 a	54.5 b	↑
Digitaria californica (LS)	0.3 b	2.5 ab	3.8 ab	6.2 a	↑
Trichloris crinita (LS)	1.2	3.5	2.7	2.8	↑
Gounia paraguayensis (ES)	1.5	2.7	0.3	0.5	↓
Aristida mendocina (ES)	2.5	1.5	1.8	0	↓
Sporobolus pyramidatus (ES)	1.7	0.7	1.2	0	↓

3.2 NDVI dynamics and ecosystem phenology

Roller-chopping reduced the integral of the NDVI by 15% and drastically shortened the length of the growing season (Table 2). The shorter growing season in disturbed sites was due to both, a significant delay in the beginning of the growing season along with an early end (Table 2). These changes in the phenology of the overall plant community were observed immediately after the disturbance and maintained for at least four years (Fig. 2). In accordance with the NDVI integral reduction, the maximum NDVI reached by a site during the season also decreased with the disturbance (Table 2). However, the moment in which that maximum NDVI occurs (Day of Max) was not affected by deforestation (Table 2). Finally, the inter-annual variation of the integral NDVI increased after deforestation (CV: 10 vs. 17% for undisturbed and disturbed sites respectively, data not shown). Before deforestation, undisturbed sites remained without significant changes in all phenological variables (exception: day of maximum NDVI), even though annual rainfall was variable among years (Table 2).

Table 2: Growing season mean values traits in undisturbed and disturbed (roller-chopping deforestation) sites. Ref: START, END and LENGTH (days) of the growing season (day 1: winter start). DAY of MAX: day of maximum Normalized Vegetation Index (NDVI). NDVI MAX: Maximum NDVI. NDVI integral. Standard deviations are shown in parenthesis.* P< 0.05, ** P< 0.01, *** P < 0.001 ns: no statistically significant difference.

Variable	Time Site	**Before disturbance**	**After disturbance**	*Time Comp*
START	**Undisturbed**	64 (3)	62 (4)	ns
	Deforested	57 (3)	97 (16)	***
	Site Comp	ns	***	
END	**Undisturbed**	349 (3)	349 (5)	ns
	Deforested	357 (2)	295 (24)	***
	Site Comp	ns	***	
LENGTH	**Undisturbed**	286 (4)	287 (6)	ns
	Deforested	299 (7)	198 (38)	***
	Site Comp	ns	***	
DAY of MAX	**Undisturbed**	215 (6)	184 (17)	**
	Deforested	214 (7)	181 (10)	**
	Site Comp	ns	ns	
NDVI MAX	**Undisturbed**	0,67 (0,01)	0,67 (0,01)	ns
	Deforested	0,67 (0,01)	0,63 (0,02)	**
	Site Comp	ns	***	
NDVI Integral	**Undisturbed**	0,53 (0,01)	0,53 (0,02)	ns
	Deforested	0,52 (0,01)	0,44 (0,01)	***
	Site Comp	ns	***	

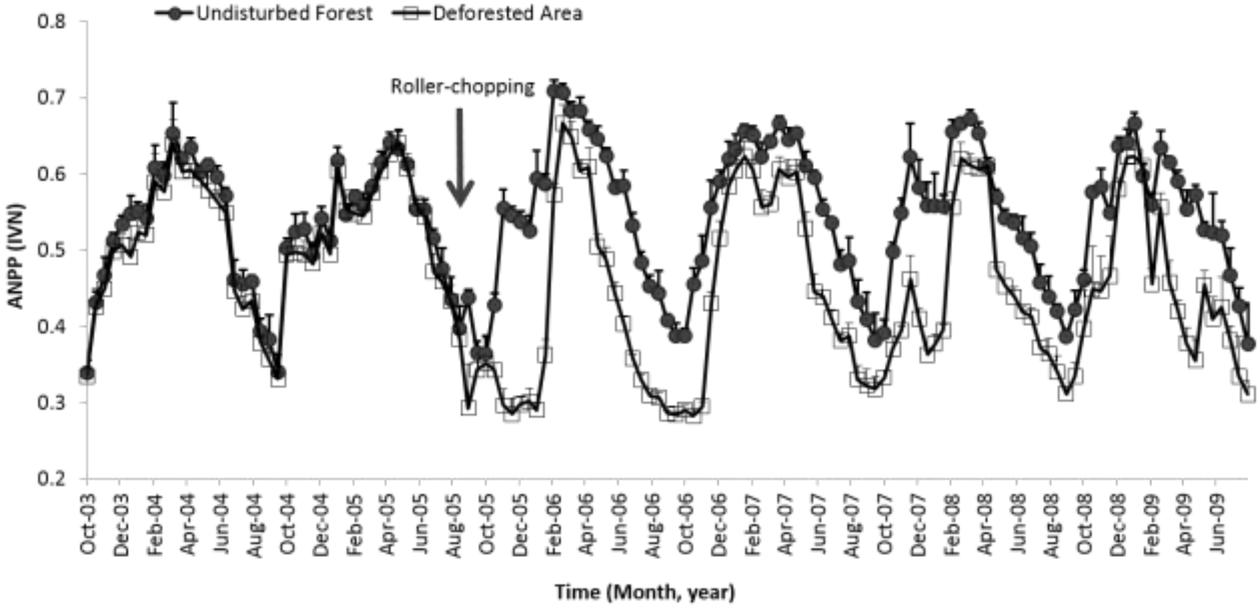

Figure 2: NDVI (mean, SE) of disturbed (white squares) and undisturbed (black circles) areas from October 2003 to July 2009. Black arrow indicates the roller chopping event.

4. DISCUSSION

Rolling-chopping deforestation modified the plant community structure, from a mainly woody to a shrubby-herbaceous system, and modified the plant ecological strategies from early to late successional species for grasses, and conversely for woody species. These changes impacted larger-scale ecosystem processes by drastically reducing the length of the growing season.

The important release of resources (e.g., light, water and nutrients) after removal of aboveground woody biomass by deforestation (Prescott, 2002; Sangha et al., 2006) seems to be capitalized by grasses that tripled their biomass in one season and maintained it during the next three seasons. Shrubs cover retrieved faster than trees after disturbance. Considering that roller-chopping cuts and chops small and medium-size woody stems but does not remove roots and buds on the base of the trunks, it seems that the greater shrub's resilience may be explained by their capacity of re-growth from remaining shoots and roots (Donato et al., 2009).

The considerable increment of forage offer immediately after roller chopping seems to improve some ecosystem conditions for example through a reduction in bare soil cover. A decrease in the proportion of bare soil and runoff after roller chopping has also been recorded by Aguilera et al. (2003) which observed that roller chopping and seeding reduced the proportion of sites susceptible to erosion (such as bare soil or short grass cover types). Despite these effects, long-term results (3-yr old patch) indicate a general impoverishment of the system by encroaching and increases of non-forage species as *Larrea* spp. and the losses of valuable forage species as *Prosopis flexuosa* which fruits are largely consumed by animals due to its high protein values (Villagra et al., 2004).

Roller chopping affected grasses and woody species in opposite ways, favoring early successional shrubs such as *Lycium chilense*, *Senna aphylla* and *Larrea divaricata*, and late successional grasses (i.e., *Digitaria californica*, *Setaria leucopila*, *Trichloris crinita*). This apparent contradiction is actually expected since the roller chopper disturbs shrubs and trees by chopping and crushing woody stems, but it does not disturb herbaceous plants. On the contrary, roller chopping increases availability of resources (i.e., nutrients, water and light) for grasses, and it may accelerate successional processes in grass communities. Resource heterogeneity also favours early successional species (Bazzaz, 1979; Bazzaz and Carlson, 1982). In our study area, as in most arid woodlands around the world, resource distribution is spatially heterogeneous (Rossi and Villagra, 2003; Abril et al., 2009), and it is attributable to shrubs and trees that creates patches of great nutrient uptake and high deposition of organic residues under their canopies (Aguiar and Sala, 1994; Prescott, 2002; Austin et al., 2004). Air and soil temperature, soil moisture and light intensity is also very heterogeneous, allowing early successional species to occupy more stressful sites (Grime, 1977). Roller chopping redistributes and homogenizes distribution of organic residues, increasing water infiltration and water-holding capacity (Aguilera et al., 2003).This more homogeneous and productive sites will allow more competitive late successional species increases their dominance.

Although shrub cover recovered with time, NDVI did not show the same trend. If we considered NDVI as a surrogate of above primary productivity (ANPP) the losses in species and functional groups diversity such as nitrogen fixers or species with deep root distribution such as *Prosopis* *flexuosa* could explain NDVI/ANPP lower values since both, species and functional groups richness has been largely shown to increment ecosystem productivity at all levels (Díaz and Cabido, 2001; Flombaum and Sala, 2008). On the other hand, changes in phenology especially during the growing and autumn seasons can have significant influence on carbon dynamics and water balance. Studies on climate change and phenology show different trends according to the nature of the disturbance, for example changes in species composition after shrubs invasion in eastern US forests have been demonstrated to extend leaf autumn phenology due to a delayed in autumn leaf fall compared with natives species (Fridley, 2012) which imply that invasive species continue assimilating carbon during these season. In addition, most of the model simulation predictions on climate change has anticipated early beginning of growing seasons as consequence of global warming and increases in precipitation (Cleland et al., 2007). Studies performed over temperate regions in China showed an advanced in the growing season on average, at a rate of 1.3 days per decade (Cong et al., 2013). Our findings, on the contrary, show a late-beginning of the growing season which could be due to the absence of trees and large shrubs with deep root distribution and rain-independent and which phenology could be more responsive to temperature than to precipitation. In areas near to our field site, studies based on the analysis of isotopic composition of plant water (δ18O and δ2H) and fluctuations of water table levels on *Prosopis* spp. site has confirmed this species as ground water dependent showing the same pattern early emergence of leaves during the dry season (Jobbágy et al., 2011). Finally, it is important to clarify that although precipitation slightly increased during the analysed period, our finding seems to be clearly the effects of deforestation than any other variable such as climate change. Additionally, the likely increment in soil moisture as a combined effect of disturbance and precipitation could even accelerate the observed process of encroachment increasing early successional shrubs *Senna aphylla* and *Larrea divarica*. By observing both, structural and functional changes after a large disturbance, this study shows the cascade effects of changing the dominance of plant life form and the changes in the abundance of plant life strategies which seems considerably affect phenology at ecosystem level.

5. ACKNOWLEDGMENTS

We are grateful to SER BEEF S.A. for providing access to its ranch and its valuable field information. This work was funded by the Argentina National Institute of Agricultural Technology (INTA) and by the Inter-American Institute for Global Change Research (IAI CRN II 2031 and CRN III 3095 supported by National Science Foundation) and the International Development Research Center (IDRC, Canada 106601-001). Especial thanks to Ruben Romero and Javier Houspanossian for their help during field campaigns. DFS, EGJ and VAM were partially supported by CONICET.

6. REFERENCES

Abril, A., Villagra, P., Noe, L., 2009. Spatiotemporal heterogeneity of soil fertility in the Central Monte desert (Argentina). Journal of Arid Environments 73, 901-906.

Aguiar, M.R., Sala, O.E., 1994. Competition, facilitation, seed distribution and the origin of patches in a Patagonian steppe. Oikos 70, 26-34.

Aguilera, M.O., Steinaker, D.F., Demaría, M.R., 2003. Runoff and soil loss in undisturbed and roller-seeded shrublands on semiarid Argentina. Journal of Range Management 56, 227-233.

Austin, A.T., Yahdjian, L., Stark, J.M., Belnap, J., Porporato, A., Norton, U., Ravetta, D.A., Schaeffer, S.M., 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141, 221-235.

Bazzaz, F.A., 1979. The Physiological Ecology of Plant Succession. Annual Review of Ecology and Systematics 10, 351-371.

Bazzaz, F.A., Carlson, R., 1982. Photosynthetic acclimation to variability in the light environment of early and late successional plants. Oecologia 54, 313-316.

Bestelmeyer, B.T., 2014. Deforestation of “Degraded” Rangelands: The Argentine Chaco Enters the Next Stage of the Anthropocene. Rangelands 36, 36-39.

Boletta, P.E., Ravelo, A.C., Planchuelo, A.M., Grilli, M., 2006. Assessing deforestation in the Argentine Chaco. Forest Ecology and Management 228, 108-114.

Canfield, R., 1941. Application of the line interception method in sampling range vegetation. Journal of Forestry 39, 388-394.

Clark, J.S., McLachlan, J.S., 2003. Stability of forest biodiversity. Nature 423, 635-638.

Cleland, E., Chuine, I., Menzel, A., Mooney, H.A., Schwartz, M., 2007. Shifting plant phenology in response to global change. Trends in Ecology and Evolution 22, 357-365.

Cong, N., Wang, T., Nan, H., Ma, Y., Wang, X., Myneni, R.B., Piao, S., 2013. Changes in satellite-derived spring vegetation green-up date and its linkage to climate in China from 1982 to 2010: a multimethod analysis. Global Change Biology 19, 881-891.

Connell, J.H., Slatyer, R.O., 1977. Mechanisms of succession in natural communities and their role in community stability and organization. American Naturalist 111, 1119-1144.

Díaz, S., Cabido, M., 2001. Vive la différence: plant functional diversity matters to ecosystem processes. Trends in Ecology and Evolution 16, 646-655.

Donato, D.C., Fontaine, J.B., Robinson, W.D., Kauffman, J.B., Law, B.E., 2009. Vegetation response to a short interval between high-severity wildfires in a mixed-evergreen forest. Journal of Ecology 97, 142-154.

Dorrough, J., Scroggie, M., 2008. Plant responses to agricultural intensification Journal of Applied Ecology 45, 1274-1283.

Eva, H., Belward, W., De Miranda, E., Di Bella, C.M., Gond, V., Jones, S., Sgrenzaroli, M., Fritz, S., 2004. A land cover map of South America. Global Change Biology 10, 731-744.

FAO, 2010. Global Forest Resources Assessment. FAO Forestry Paper 163, Rome.

Fernández, R., Maseda, P., 2006. Ecofisiología de Arbustivas: reconocimiento de síndromes para un mejor diagnóstico de la situación de arbustización Jornadas de actualización técnica "Control y Manejo del renoval". INTA-CREA, Santiago del Estero, Argentina, pp. 47-55.

Flombaum, P., Sala, O.E., 2008. Higher effect of plant species diversity on productivity in natural than artificial ecosystems. Proceedings of the National Academy of Sciences of the United States of America 105, 6087-6090.

Fridley, J.D., 2012. Extended leaf phenology and the autumn niche in deciduous forest invasions. Nature 485, 359-362.

Gasparri, N.I., Grau, H.R., Gutiérrez Angonese, J., 2013. Linkages between soybean and neotropical deforestation: Coupling and transient decoupling dynamics in a multi-decadal analysis. Global Environmental Change 23, 1605-1614.

Grime, J.P., 1977. Evidence for the Existence of Three Primary Strategies in Plants and Its Relevance to Ecological and Evolutionary Theory. The American Naturalist 111, 1169-1194.

Guariguata, M.R., Ostertag, R., 2001. Neotropical secondary forest succession: changes in structural and functional characteristics. Forest Ecology and Management 148, 185-206.

Hoyos, L.E., Cingolani, A.M., Zak, M.R., Vaieretti, M.V., Gorla, D.E., Cabido, M.R., 2013. Deforestation and precipitation patterns in the arid Chaco forests of central Argentina. Applied Vegetation Science 16, 260-271.

Jobbágy, E. G., O. E. Sala, and J. M. Paruelo. 2002. Patterns and Controls of Primary Production in the Patagonian Steppe: A Remote Sensing Approach. Ecology 83:307-319.

Jobbágy, E.G., Nosetto, M.D., Villagra, P.E., Jackson, R.B., 2011. Water subsidies from mountains to deserts: their role in sustaining groundwater-fed oases in a sandy landscape. Ecological Applications 21, 678-694.

Jönsson, P., Eklundh, L., 2004. TIMESAT - A program for analyzing time-series of satellite sensor data. Computers and Geosciences 30, 833-845.

Kirby, J., Kingham, R., Cortes, M., 2001. Texture, density and hydraulic conductivity of some soils in San Luis province, Argentina. Ciencia del Suelo 19, 20-29.

Körner, C., Basler, D., 2010. Phenology Under Global Warming. Science 327, 1461-1462.

Kunst, C., Ledesma, R., Bravo, S., Albanesi, A., Anriquez, A., van Meer, H., Godoy, J., 2012. Disrupting woody steady states in the Chaco region (Argentina): Responses to combined disturbance treatments. Ecological Engineering 42, 42-53.

Leniére, A., Houle, G., 2009. Short-term responses of the understory to the removal of plant functional groups in the cold temperate deciduous forest. Plant Ecology 201, 235-245.

Lohbeck, M., Poorter, L., Paz, H., Pla, L., van Breugel, M., Martínez-Ramos, M., Bongers, F., 2012. Functional diversity changes during tropical forest succession. Perspectives in Plant Ecology, Evolution and Systematics 14, 89-96.

Lohbeck, M., Poorter, L., Martínez-Ramos, M., Bongers, F., 2014a. Biomass is the main driver of changes in ecosystem process rates during tropical forest succession. Ecology 96, 1242-1252.

Lohbeck, M., Poorter, L., Martínez-Ramos, M., Rodriguez-Velázquez, J., van Breugel, M., Bongers, F., 2014b. Changing drivers of species dominance during tropical forest succession. Functional Ecology 28, 1052-1058.

Morello, J., 1955. Estudios botánicos en las regiones áridas de Argentina (II). Revista Agronómica Noroeste Argentino 1, 385-524.

Morello, J., 1958. La Provincia Fitogeográfica del Monte Instituto Miguel Lillo-Universidad Nacional de Tucumán, Tucumán, Argentina.

Noble, I.R., Slatyer, R.O., 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio 43, 5-21.

Oesterheld, M., 2005. Los cambios de la agricultura Argentina y sus consecuencias. Ciencia Hoy 15, 6-12.

Prescott, C.E., 2002. The influence of the forest canopy on nutrient cycling. Tree physiology 22, 1193-1200.

Rossi, B.E., Villagra, P.E., 2003. Effects of Prosopis flexuosa on soil properties and the spatial pattern of understorey species in arid Argentina. Journal of Vegetation Science 14, 543-550.

Rueda, C.V., Baldi, G., Verón, S.R., Jobbágy, E.G., 2013. Apropiación humana de la producción primaria en el Chaco Seco. Ecología Austral 23, 44-54.

Sangha, K.K., Jalota, R.K., Midmore, D.J., 2006. Litter production, decomposition and nutrient release in cleared and uncleared pasture systems of central Queensland, Australia. Journal of Tropical Ecology 22, 177-189.

Staus, N., Strittholt, J., DellaSala, D., Robinson, R., 2002. Rate and pattern of forest disturbance in the Klamath-Siskiyou ecoregion, USA between 1972 and 1992. Landscape Ecology 17, 455-470.

Tilman, D., 1997. Biodiversity and ecosystem functioning, in: Daily, G. (Ed.), Nature´s Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, pp. 93-112.

Viglizzo, E.F., Frank, F.C., Carreño, L.V., Jobbágy, E.G., Pereyra, H., Clatt, J., Pincén, D., Riccard, M.F., 2010. Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. Global Change Biology 17, 959-973.

Villagra, P.E., Cony, M.A., Mantován, N.G., Rossi, B.E., 2004. Ecología y manejo de los algarrobales de la provincia fitogeográfica del monte, in: Frangi, J., Goya, J. (Eds.), Ecología y manejo de bosques nativos de Argentina. Universidad de la Plata, pp. 3-32.

White, P.S., 1979. Pattern, process, and natural disturbance in vegetation. The Botanical Review 45, 229-299.

Zak, M.R., Cabido, M., Caceres, D., Diaz, S., 2008. What drives accelerated land cover change in central Argentina? Synergistic consequences of climatic, socioeconomic, and technological factors. Environmental Management 42, 181-189.