

The impact of afforestation on ecosystem functioning on grassland areas of temperate South America

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Abstract - Because of the contrasting structure and ecophysiology of grasses and trees, grassland-forest transitions are likely to impact deeply on ecosystem matter and energy exchange patterns. We evaluated the effect of the afforestation of native grassland areas of temperate South America on the dynamics of carbon and water fluxes. We selected 9 pairs of grassland and tree plantation stands along a precipitation gradient ranging 550 to 1200 mm/year. We used Normalized Difference Vegetation Index (NDVI) and Surface temperature (Ts) from NOAA/AVHRR LAC (1x1 km.) to estimate intercepted photosynthetic active radiation, a surrogate of net primary production (NPP), and evapotranspiration (Et). Annual average NDVI increased 4 to 41 % and ANPP increased between 26 and 256% after afforestation with changes becoming larger towards the humid end of the precipitation gradients. Annual Et was 20 to 110 mm/yr higher in afforested plots. Two plots showed a reduction in Et in the afforested plots. Afforestation had a strong effect on water and carbon fluxes regulated by precipitation at the regional scale.

I. INTRODUCTION

Today most of our knowledge on the ecosystem functioning of grassland-forest transitions derives from situations in which native forest ecosystems are replaced by secondary grasslands or pastures (McGrath et al. 2001). The effect of the opposite trajectory, afforestation and tree encroachment of native grasslands has been poorly explored.

Tree plantations have been established into the treeless grasslands of southern South America since the mid 1800s to the present. Today, plantations for wood, shade, and windbreak spread all over the region. While larger afforestation projects are being launched or planned by companies and local

governments, the regional impact of such land use change remains poorly understood.

Carbon and water fluxes are key aspects of ecosystem function that can be derived from satellite data. The fraction of the photosynthetic active radiation intercepted by the canopy (FPAR) and the evapotranspiration (ET) can be estimated with satellite-born radiometers. The annual integral of the Normalized Difference Vegetation Index (NDVI), a spectral index based on red and infrared reflectance, is strongly correlated with intercepted photosynthetic active radiation (IPAR) and hence with ANPP (Box et al., 1989; Kennedy, 1989; Prince, 1990, Paruelo et al. 1997, Paruelo et al. 2000). Reliable estimates of evapotranspiration can be derived from satellite data by modeling the energy balance of the land surface (Sobrino and Raissouni 2000, DiBella et al. 2000; Running and Nemani, 1988). Such models combined NDVI and surface temperature, derived from thermal infrared bands.

The objective of this study was to evaluate the effect of the afforestation of native grassland areas of temperate South America on the dynamics of carbon and water fluxes.

II. METHODOLOGY

We identified commercial forested plots within the Rio de la Plata grasslands in Argentina and Uruguay (figure 1) using Landsat TM images and selected those larger than 500 ha. Sites encompassed 550 to 1200 mm/year of precipitation and 14.5 to 19 °C of mean annual temperature over a variety of soil types (table 1). We select 9 areas with 6 to 20 km² paired

plots of managed grassland and planted forest with either *Eucalyptus* or *Pinus* species.

Table 1. Description of the study sites. MAP is mean annual precipitation (mm/yr) and MAT is mean annual temperature (°C) both interpolated from FAO data (1985). The species and soils (INTA-SAGYP 1990, Ministerio de Agricultura y Pesca, 1979) are the predominant in each site.

Site	MAP	MAT	Species	Soils
Ca1	550	17.7	<i>Pinus</i>	Udtort/Udipsamentes
RiC	597	17.1	<i>Pinus</i>	Udtort/Udipsamentes
Pil	881	15	<i>Eucalyptus</i>	Argi/Natracuol
Car	837	14.5	<i>Pinus</i>	Udipsamentes
Co1	1236	18.9	<i>Eucalyptus</i>	Peludert
Co2	1119	19	<i>Pinus</i>	Hapludol
Pa1	1280	18.9	<i>Eucalyptus</i> - <i>Pinus</i>	Argiudol-Hapludalf
Pa2	1280	18.9	<i>Eucalyptus</i> - <i>Pinus</i>	Argiudol-Hapludalf
Pa3	1280	18.9	<i>Eucalyptus</i> - <i>Pinus</i>	Argiudol-Hapludalf

We use the Normalized Difference Vegetation Index (NDVI) for the period 1992-93 and 1995-2001, and surface temperature (Ts) for the period 1992-93. NDVI and Ts were derived from NOAA/AVHRR LAC (1x1 km) ten-day composites. Ts was calculated from channel 4 (10.3-11.3 mm) and corrected by surface emissivity using NDVI and channel 5 (11.5-12.5 mm) (see Sobrino et al. 1991). We use these spectral data to estimate the IPAR, a surrogate of primary productivity, and the actual evapotranspiration (Et). We derived, from the NDVI seasonal curves, the annual NDVI average (NDVI-I) an estimator of the total amount of radiation intercepted by the canopies throughout the growing season.

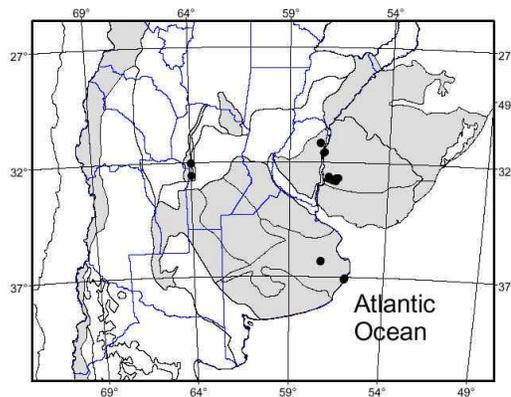


Fig. 1. Location of studied sites. Shaded areas denote grasslands in Argentina, Uruguay and Brazil (Soriano 1991). Dark points indicate the studied sites.

We estimated IPAR as:

$$\text{IPAR (MJ/ha.year)} = \text{PAR} \times \text{fPAR}$$

PAR is the photosynthetic active radiation and was obtained by interpolation of data from FAO (1985).

fPAR was calculated from NDVI ($\text{fPAR} = -0.025 + 1.25 \times \text{NDVI}$, Ruimy et al 1994)

Monthly actual evapotranspiration was estimated as $\text{NDVI (monthly)} \times \text{Et (monthly)} \times 5.831$ (Garbulsky and Paruelo, in preparation).

III. RESULTS

Afforestation increased the average annual NDVI-I of grasslands between 4 and 41 % for a seven-year period (fig. 2). The Atlantic coastal sand dunes (Car) presented the maximum relative difference. Minimum differences were observed in the mountain grassland of Ca1 and RiC and on the Vertisols of Co1. The interannual variability of these differences was low, as show by the standard error bars in figure 2. NDVI-I was no more than 0.05 higher in grasslands Negative differences (NDVI-I forestation- NDVI-I grassland < 0).

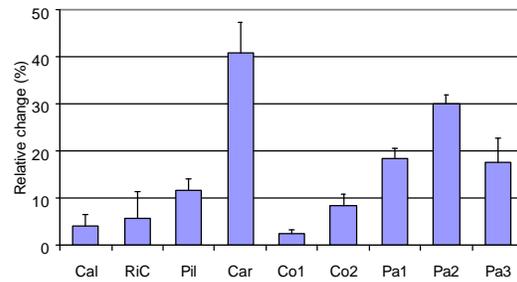


Figure 2. Relative change of the annual average NDVI-I between forests and grasslands. Relative change was calculated as $(\text{NDVI-I forests} - \text{NDVI-I grasslands}) \times 100 / (\text{NDVI-I grasslands})$. Error bars show the standard error between seven growing seasons.

Afforestation generated an average reduction of 0.85°C on the Ts (fig. 3). Only one site presented a positive change on Ts, probably related with the young age of the plantation.

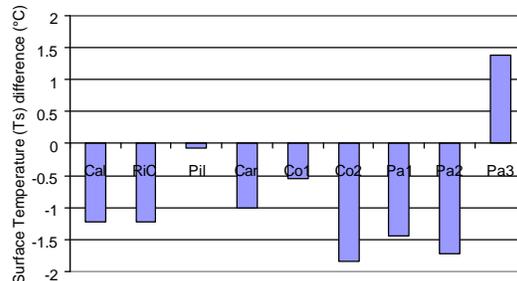


Figure 3. Average annual surface temperature differences between afforestations and grasslands for the period 1992-93.

IPAR increased in all the areas due to land use change to afforestation (fig. 4). Relationship between IPAR and MAP for each land use presented two linear regressions ($p < 0.001$). The amount of

PAR intercepted per mm of precipitation did not differ statistically among land uses. It ranged from 0.75 MJ.m⁻².yr⁻¹ for grasslands to 1.02 MJ.m⁻².yr⁻¹ for forested areas. The relative change in IPAR due to land use did not correlate with precipitation.

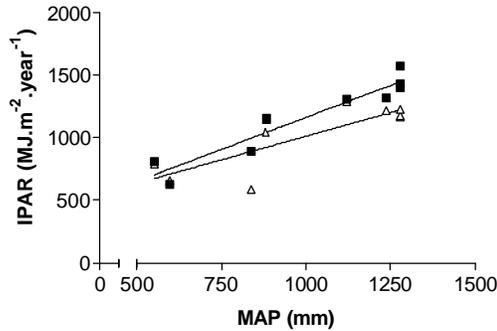


Figure 4. Relationship between annual intercepted photosynthetic active radiation and mean annual precipitation for afforestation (■) and grassland (△) sites. Lines show the regression for each land use (grasslands: $IPAR = 258.5 + 0.75 \times MAP$, $r^2 = 0.71$, $p < 0.01$; forests: $IPAR = 140.2 + 1.02 \times MAP$; $r^2 = 0.90$; $p < 0.0001$; $n=9$)

The average evapotranspiration of grasslands was 750mm/yr. Afforestation increased annual actual evapotranspiration between 20 and 110 mm/yr (fig. 5). Two areas presented negative changes and one did not present significant changes (Pa3).

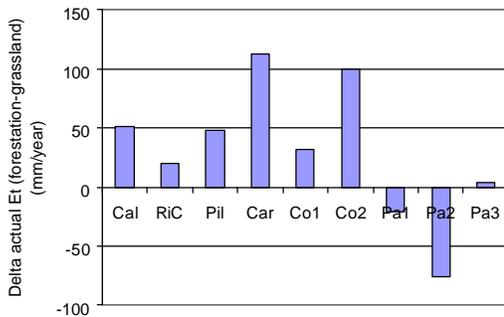


Figure 5. Afforestation impact on the annual actual evapotranspiration (mm/yr) for 1992-93, estimated from NOAA/AVHRR data in nine sites across the Rio de la Plata grasslands.

IV. DISCUSSION

Our results suggest that afforestation has generated important effects on water and carbon cycles of grassland ecosystems in temperate South America.

The differences presented in IPAR can be transformed to ANPP using the model proposed by Monteith (1977): $ANPP (g DM/ha. yr) = IPAR \times \epsilon$

where ϵ denotes the conversion efficiency of radiation into dry matter. Using ϵ values from the literature (Ruimy et al 1994, Paruelo et al. 1997), our estimations of ANPP ranged between 300 to 2000 g.m⁻².yr⁻¹ of dry matter for forestations and 200 to 700 for grasslands. These results greatly agree with ANPP estimations derived from other methods (Sala et al, 1988, Pucheta et al 1998, Berretta 1994, Cozzo and Rivero 1969, Dalla-Tea and Marcó, 1996).

ANPP positively increased due to land use change along the precipitation gradient between 26 and 256%. The impact of afforestation on ecosystem functioning was greatly controlled by precipitation. 84% of the variability in the relative change in ANPP was explained by the regional gradient of mean annual precipitation (ANPP Relative change (%) = $0.24 \times MAP - 97.8$; $r^2 = 0.84$; $p < 0.001$; $n = 9$).

The universal relationship between the ANPP of grassland ecosystems and precipitation (Sala et al. 1988) did not hold after tree establishment. Tree dominated systems tend to be more productive than grasslands as precipitation increased. This suggests vegetation structure as well as climate is a key control of ANPP.

The inclusion of belowground net primary productivity (BNPP) is needed to conclude about the impacts of the afforestation on the ecosystem carbon fluxes. We estimate BNPP using below/above-ground primary productivity allocation ratios found in the literature (0.2 in cultivated forests and 1.5 in the flooding pampas grasslands; Ruimy et al 1994 and Deregius et al, 1982 respectively). BNPP was higher in grasslands along the precipitation gradient and this make the total primary productivity figures much closer between both land uses. Maximum differences of 1000 g.m²/yr arose in the humid extreme of the precipitation gradient.

Effects of afforestation on primary productivity were greater than in IPAR and NDVI-I because of the higher total radiation in wet sites and of the change to higher radiation use efficiencies of woody vegetation compared to grasslands. These results highlight the importance of transforming basic spectral data into biologically meaningful variables such as ANPP in order to assess ecosystem functional changes. We highlight the importance of a proper definition of ϵ values for different canopies. Uncertainties yet rely on their definition.

The impact on water cycles shows that forestation uses more water than grasslands. The most dramatic change occurred in the Udipsaments in Car, where the afforestation increased the evapotranspiration

36% compared with that of the grassland. However, these results could underestimate the real impact of afforestation compared with other methods estimations (E.G. Jobbagy, personal communication). Widespread afforestation of these grasslands would probably modify the above and belowground water cycles and could severely deplete freshwater supplies for other purposes.

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