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Grassland afforestation: towards an integrative perspective of its ecological oportunities and costs

Forestación en pastizales: hacia una visión integral de sus oportunidades y costos ecológicos

Jobbágy, E.[1]; Vasallo, M.[2]; Farley, K.[3]; Piñeiro, G.[2]; Garbulsky, M.[2]; Nosetto, M.[4]; Jackson, R.[5]; Paruelo, J.[2]

[1]*Grupo de Estudios Ambientales – IMASL, Universidad Nacional de San Luis & CONICET, San Luis, Argentina*
[2]*Universidad de Buenos Aires, Facultad de Agronomía, Laboratorio de Análisis Regional y Teledetección – IFEVA, Ciudad de Buenos Aires, Argentina*
[3]*Center on Global Change, Duke University, Durham, United States*
[4]*Universidad Nacional de San Luis & CONICET, Grupo de Estudios Ambientales – IMASL, San Luis, Argentina*
[5]*Duke University, Department of Biology and Nicholas School of the Environment and Earth Sciences, Durham, United States*

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Abstract

The establishment of tree plantations on native grasslands is expanding in Argentina and Uruguay, prometed by public incentives and, likely, by an emerging market of carbon sequestration. We assessed how this transformation affects the production of ecosystem goods and services, synthesizing preexisting and original information on their influence on biomass production, water dynamics, and nutrient cycling. Field and satellite measurements show that, compared to grasslands, tree plantations in Uruguay, Entre Ríos, and Corrientes had higher primary productivity. This productivity increase was accompanied by higher evapotranspiration rates and a lower water yield, responsible of halving stream flow in afforested watersheds in Córdoba and Uruguay, in agreement with observations on 26 afforested grasslands around the world. In Buenos Aires, where phreatic water is close to the surface, trees used groundwater increasing the salinity of deep soil and the water table. Most of the tree plantations in the region acidified soils and in some cases stream water, mainly as a result of their high calcium consumption. It is urgent to generate information about other impacts of tree plantations such as changes in fire dynamics or invasive species. An integrative understanding of the influence of tree plantations on the production of goods and services will help to development new forestry systems and policies that are more sustainable and useful for society.

Keywords: carbon sequestration, hydrological cycle, land use change, soil acidification, tree plantation

Resumen

El establecimiento de plantaciones forestales sobre pastizales se expande en Argentina y Uruguay, incentivado por los altos rendimientos, el apoyo fiscal y posiblemente por el inminente comercio de bonos de carbono. Evaluamos como esta transformación afecta la producción de bienes y servicios de los ecosistemas, sintetizando información preexistente y original acerca de su influencia sobre la producción de biomasa y la dinámica del agua y la circulación de nutrientes. Mediciones de campo y satelitales muestran que la productividad primaria de las plantaciones forestales en Uruguay, Corrientes y Entre Ríos superó a la de los pastizales. Este aumento en la productividad fue acompañado por una mayor

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evapotranspiración y un menor rendimiento hidrológico que redujo a la mitad el caudal de cuencas forestadas en Córdoba y Uruguay, en acuerdo con lo observado en 26 pastizales forestados de todo el mundo. En Buenos Aires, donde el agua freática se encuentra cerca de la superficie, los árboles pueden utilizar agua subterránea, salinizando suelos y napas. Las plantaciones forestales en la mayoría de los pastizales de la región acidifican el suelo y en algunos casos el agua de los arroyos, principalmente debido al elevado consumo de calcio. Es apremiante generar información acerca de otros impactos de las forestaciones tales como cambios en la dinámica del fuego y el avance de especies invasoras. Reconocer integralmente la influencia de las forestaciones sobre la producción de servicios y bienes permitirá plantear sistemas y políticas forestales más sustentables y útiles para la sociedad.

Palabras clave: acidificación del suelo, cambio en el uso de la tierra, ciclo hidrológico, plantación forestal, secuestro de carbono

Introduction

Transitions between grassland-dominated and tree-dominated systems often have a major impact on ecosystem functioning as a result of the contrast that these two large groups of plants exhibit concerning energy, water, and nutrient usage. While the transformation of large areas occupied by natural forests into pastures and crops (for example, the advance of livestock farming and agriculture over the Amazon forests) is the most recognized, studied, and discussed case of this type of transition (e.g.: Nepstad and others, 1994, Rudel & Ropel 1996, McGrath and others, 2001, Cerri and others, 2004,) the opposite change, i.e. the establishment of trees in originally herbaceous systems, acquires great importance today through the expansion of forest plantations on grassland areas (Richardson 1998; Geary 2001).

Plantations of fast-growing species such as pines and eucalyptus, common in many areas initially occupied by natural grasslands, especially in the southern hemisphere, are now transformed into a locally important type of land use, replacing natural forests in many economies as the main sources of forest products (FAO 2005). In the case of a nation occupied mainly by grasslands such as Uruguay, this is evidenced by the triplication of the forested area in the nineties, with the area covered by plantations exceeding 700,000 ha today (FAO 2005). The possible consolidation and growth of the carbon credits market, stimulated by the entry into force of the Kyoto protocol, can generate an additional incentive for this activity that, in many countries, such as Argentina and Uruguay, has received a strong stimulus through subsidy and tax reimbursement plans for more than two decades (Wright and others, 2000).

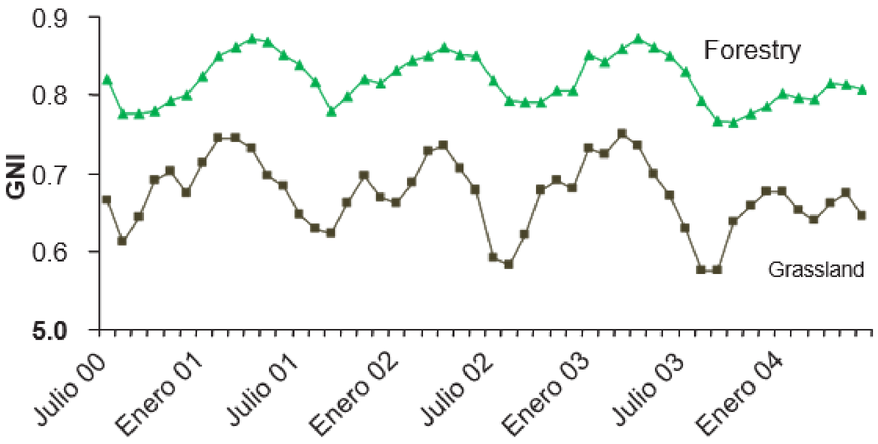
The Rio de la Plata grasslands in Uruguay and Argentina are home to some of the continent's fastest-growing forest hotspots. The advance of forestry activity on land originally dedicated to livestock and, to a lesser extent, to agriculture, rethinks its productive potential and forces to recognize its influence on the generation of drinking water, hydrological regulation, maintenance of soil fertility, or the sequestration of carbon dioxide; among other natural services that, although they do not have a price in the market today, have an indisputable value for society (Panario 1991, Paruelo 2006).

This article summarizes the knowledge advance in the ecology of the forests established on grasslands achieved by a team of researchers from Argentina, Uruguay and the United States in the last six years. Three central aspects of changes in grassland functioning after afforestation are highlighted: (1) biomass production and carbon accumulation, (2) water use and hydrological impact, and (3) nutrient uptake and its influence on soil fertility. Towards the end (4) an alternative forest system for the grasslands of the region is proposed, and (5) outstanding questions and paths to follow in the research of these systems are discussed.

Primary production and carbon dynamics

The net primary productivity of an ecosystem, defined as its ability to generate plant biomass, is one of its key attributes, from both an agricultural and ecological point of view (McNaughton and others, 1989, Schlesinger 1997) and also, as we illustrate below, one of the most influenced when forest plantations replace grasslands. An expeditious way to characterize the primary production of a terrestrial ecosystem is through the use of spectral indices that use the energy reflected by the surface to quantify the photosynthetic activity of ecosystems using satellite-mounted sensors. The green normalized index (GNI) is particularly effective. This index combines the reflectance values in the visible and near-infrared bands of the spectrum generating values that approximate one when the photosynthetic activity and, therefore, the primary productivity is maximum and at 0 when it is null (Tucker & Sellers 1986, Paruelo and others, 1997, Jobbágy and others, 2002). An analysis of the dynamics of the GNI obtained from MODIS images in 181 forested sectors and adjacent non-forested areas of the grasslands of Uruguay and the provinces of Corrientes and Entre Ríos in Argentina, during four growing seasons (July 2000 to June 2004), suggested an important contrast in the dynamics of primary production with large increases in the intensity of this process in forested areas (Fig. 1).

Figure 1. Dynamics of the standard green index (GNI), satellite indicator of the level of primary production, for forest plantations and adjacent non-forested areas (grassland). The data illustrate the average obtained for 181 pairs of stands from Uruguay and the Argentine provinces of Corrientes and Entre Ríos. Monthly data derived from the MODIS-TERRA platform with a spatial resolution of 250 x 250 m were used.



All the pairs analyzed showed higher GNI (average for the four years) in afforestation than in grassland, with an average increase of approximately 22%. The average curve of all afforestations showed higher values than that of grasslands throughout the analysis period, showing maximum differences during the winter and delays of approximately one month at the time of occurrence of the maximum and minimum photosynthetic activity (Fig. 1). These patterns, based on satellite data, are affirmed by the few field measurements of aboveground net primary production (fraction of biomass produced aboveground: stems, leaves, etc.) available for the same study area. Thirteen studies suggest that grasslands reach average productivity (dry matter) of 5100 kg ha^{-1} year^{-1} (range 2400 to 9800 kg ha^{-1} year^{-1}, Deregibus and others, 1987, Pizzio 1993, Maraschin and others, 1997, Paruelo and others, 2000, Formoso and others, 2001, Nordenstahl 2005, Altesor and others, 2005, Piñeiro and others, 2006), while equivalent measurements for forests in Entre Ríos indicate values between 19200 and 24900 kg ha^{-1} year^{-1} according to soil type (Goya and others,1997).

Therefore, it is evident that afforestation achieves higher growth rates or carbon gains than the grasslands they replace, and this is, possibly, one of the most relevant ecological incentives and opportunities of afforestation.

Forestry also allows a more exhaustive use of primary production by allocating a smaller fraction of it to underground structures that cannot be harvested (typically the ratio between aboveground and underground biomass in rainforests and plantations is close to 5:1, while in grasslands the ratio is usually lower than 1:2, Cairns and others, 1997, Jackson and others, 1997, Jobbágy & Jackson 2000). However, this advantage can become negative from the perspective of carbon sequestration and its accumulation in the soil as organic matter, since it depends mainly on biomass inputs via roots (especially at depth - Jobbágy & Jackson 2000).

From the perspective of carbon storage and sequestration, of increasing interest today, it is also necessary to ask whether the largest primary production achieved by forestry can be capitalized on greater carbon reserves, both in the plant biomass and in the organic matter of the soils. In this sense, it is important to separate the carbon gain of the ecosystem from the total amount of carbon that the ecosystem eventually manages to store, which will depend on the balance of the ecosystem between carbon gains and losses (total respiration, herbivory, harvest).

In terms of plant biomass, the higher carbon gains are clearly capitalized in higher biomass accumulations in tree trunks and, to a lesser extent, in the thicker roots of trees, whose average life is much longer than that of herbaceous plants. Regarding the soil, some local evidence (Jobbágy & Jackson 2003, Nosetto and others*,* 2006, Delgado and others*,* 2006) and synthesis of studies carried out worldwide (Paul and others*,* 2002) indicate that the mineral soil of pastures would not generally gain organic matter after being forested and that the soil could lose carbon in wet systems such as those of Uruguay (Jackson and others*,* 2002, Kirschbaum and others*,* 2006). However, mulch accumulation and organic horizons formation on the soil surface could hold significant amounts of carbon, similar to the year-long productivity in forests (Jobbágy & Jackson 2003, Delgado and others*,* 2006). An in-depth analysis of the potential offsetting of greenhouse gas emissions by land-use changes to assess with certainty the role of forestry and grasslands should consider the residence time of carbon in the ecosystem once fixed. In this sense, it would be useful to weigh differentially the stable carbon held in soil´s organic matter, to that residing in the biomass that can return to the atmosphere after being used as fuelwood, food, or raw material for industries after combustion.

Apart from the purely economic and political incentives that have promoted forestry, the possibility of achieving high biomass yields on grasslands has been a key stimulus for its expansion. The presence of natural grasslands in the region is fundamentally associated with the existence of different degrees of limitations for agriculture (rockiness, flooding, salinity, very sandy or clayey substrates, etc.,) since, in situations of optimal agricultural suitability, grasslands were replaced by crops in most cases. As shown in the satellite analysis of forested grassland areas, the lower agricultural suitability has not implied low forest productivity. Instead, it has offered the possibility of achieving good yields in regions traditionally restricted to livestock, with lower land value than agricultural lands.

The high level of primary production of the forests established in the Río de la Plata grasslands and their greater accumulation of plant biomass opens opportunities for the generation of primary goods and for the sequestration of atmospheric carbon dioxide, an ecosystem service likely to acquire market value in a few years (Wright and others*,* 2000).

However, the indivisible connection between carbon, water, and nutrient cycles in ecosystems allows questioning how these increases in primary production would propagate to hydrological dynamics and soil fertility (Fig. 2).

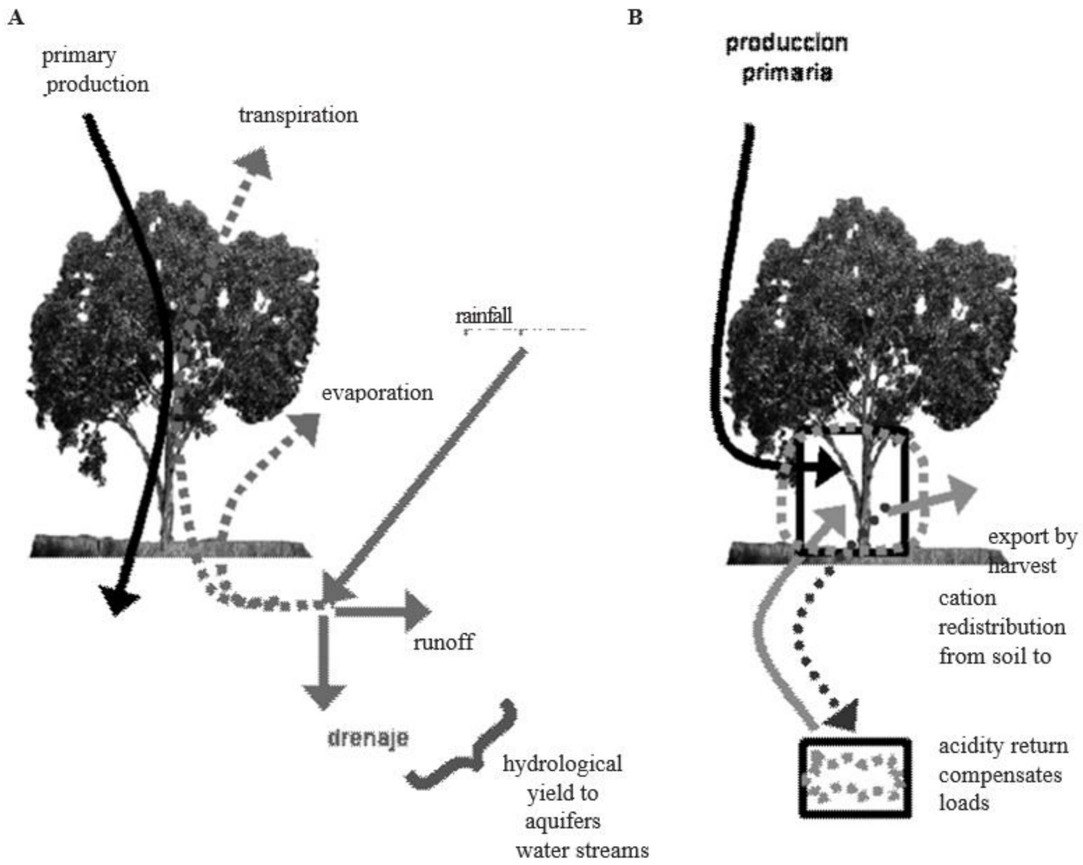
Water dynamics and hydrological impact

The capture of atmospheric carbon by plants is intimately linked to the reciprocal exchange of water with the atmosphere, a process known as transpiration (Fig. 2A). In general, higher rates of carbon fixation are associated with higher transpirational water loss. Meanwhile, increases in transpiration rates under equal precipitation conditions restrict the water available for other water flows. This occurs mainly on liquid water outflows (surface runoff or deep drainage), which are responsible for aquifer recharge and stream feeding (hydrological yield) (Fig. 2A). It can then be expected that increases in productivity associated with grassland forestry will be accompanied by increases in transpiration and decreases in hydrological yield. We have investigated these possible changes from three independent approaches. First, from a global review and local study of changes in streamflow in afforested grassland watersheds. Secondly, from satellite studies of evaporative water losses in afforested and grasslands in Entre Ríos. Finally, through field evaluations of aquifer dynamics in afforested areas of the province of Buenos Aires.

Based on a comprehensive review of scientific literature and technical reports from around the world, we identified studies that evaluated possible changes in the flow delivered by small watersheds in afforested grassland and native shrub regions. The studies selected were those in which the flow was monitored in paired forestry watersheds (mainly pines and eucalyptus trees) and controls under natural vegetation (in this regard see Farley and others). In the 26 pairs analyzed, from four continents, 504 observations of annual flow were included. In this dataset it was observed that on average grassland and shrub forestry reduced absolute values of hydrological yield by 39% (167 mm/year), causing complete flow reduction for at least one year in 13% of cases (Farley and others*,* 2005). Forestry impacts on the flow were stronger, in terms of relative decline, under drier climates.

This is because in these areas the fraction of rain reaching streams is already low and therefore small increases in evapotranspiration can cause big changes in hydrological yield (Zhang and others*,* 2001, Farley and others*,* 2005). It is interesting to note that flow reductions were more important in eucalyptus plantations than in pine plantations, with drops in the absolute value of hydrological yield of 50 and 30%, respectively.

Figure 2. Coupling between carbon dynamics and water and nutrients. A) Carbon dioxide entry through the plant stomata occurs along with transpiration water loss. Higher carbon fixation and primary productivity in forestry than in grasslands would be linked to higher transpiration rates, especially considering that forestry is not less efficient in using water than the grasslands they replace. Increased transpiration subtracts water available for other flows, such as deep drainage and runoff, responsible for feeding rivers and aquifers. B) Carbon accumulation in biomass occurs along with the capture of nutrients in tissues. In the case of calcium and forestry, this is particularly important since this nutrient, which is scarce in herbaceous tissues, accumulates in greater concentration in wood, especially eucalyptus. Calcium gains in biomass can cause significant losses of calcium in soil and produce acidification.



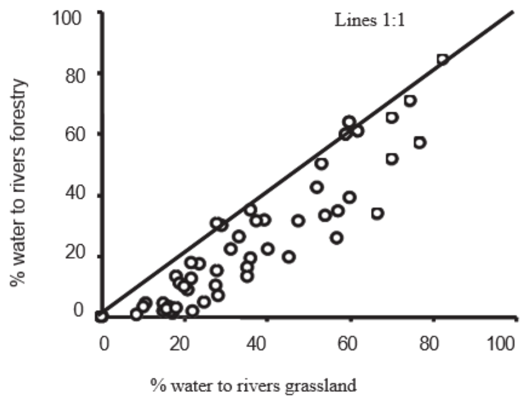
When this information is analyzed considering the proportion of rainwater entry reaching the streams (fraction of hydrological yield) under each pair of natural grassland or shrub vs forestry, it is observed that in very few cases this fraction remains constant, being the average reduction of all pairs of 15% (percentage of annual rainfall that stops reaching the water courses) (Fig. 3).

This implies that, in general terms, in grasslands where 30% of rainfall translates into hydrological yield, forestry will reduce flows by half, while in places where this initial yield is only 15%, the flow reduction could be total.

In the specific case of the Rio de la Plata grasslands, preliminary information based on specific flow measurements in paired watersheds in Lavalleja (8 pairs, 4 dates) and Cordoba (4 pairs, 5 dates) suggest reductions in flow close to 50% after the establishment of forestry (Piñeiro, Jobbágy, Farley & Jackson – unpublished data). Research in northern Uruguay carried out in a natural grassland macro-watershed of ~2000 km^2 show that the fraction of annual hydrological yield, and especially the summer one, decreased after the establishment of eucalyptus trees in a quarter of its surface (Silveira & Alonso 2004, Silveira and others, 2006).

Satellite imagery allows the estimation of water vapor loss rates from ecosystems by combining visible, near-infrared and thermal-infrared spectral information from the surface with local meteorological measurements. These estimates integrate direct soil evaporation with plant transpiration (evapotranspiration, see Fig 2A) (Nosetto and others, 2005). Using images of LANDSAT satellites for seven dates covering a wide range of climatic conditions, we estimated the evapotranspiration of 117 plots covered by forests or grasslands in the Concordia region in Entre Ríos, Argentina (Nosetto and others, 2005). Despite their higher radiation absorption (lower albedo), the forestry had lower canopy temperatures than the grasslands (∆= 5ºC on average), which would be explained by 80% higher evapotranspiration rates in the former (Nosetto and others, 2005).

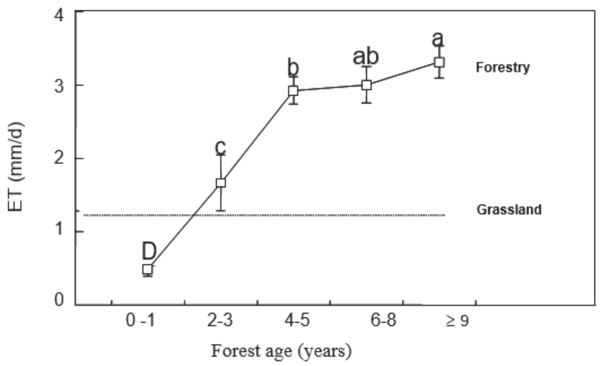
Figure 3. Changes in rainfall partitioning towards small rivers and streams in watersheds that have been forested vs. control watersheds that are kept under natural grassland or shrub vegetation. The points represent annual measurements in 26 pairs of watersheds worldwide for one or more years and the values correspond to the percentage of annual rainfall reaching the streams (hydrological yield), a value that can be considered complementary to that of evapotranspiration losses since these watersheds would not exchange water with others or with large underlying aquifers. Data extracted from Farley and others, 2005.



The average daily evapotranspiration rates obtained for plantations of different ages suggest that in only two years forestry exceeds the evaporative capacity of the grasslands and that in only 4-5 years they at least double it (Fig. 4). This information indicates that even if a significant fraction of the forested area of a region is in early stages of forest rotation (recent implantation or regrowth), it will very soon be evapotranspirating more than grassland and therefore generating a lower hydrological yield than grassland. If the results of the satellite analysis are projected to the annual scale, it is found that of the 1350 mm/year provided by rainfall, a hydrological yield of 720 mm/year would be obtained under grassland and 200 mm/year under forestry (Nosetto and others, 2005). This fall, greater than 70%, could locally affect consumers of drinking water, and hydropower at the regional level.

In situations where groundwater is close to the surface, as is the case of much of Argentina's Pampa Húmeda, the establishment of forestry in grassland can not only limit the recharge of aquifers but also begin their discharge by absorption and transpiration of groundwater. The exploration of soils and water tables in forested areas in the pampa has shown a generalized process of salinization accompanying the plantation of different species of trees (Jobbágy & Jackson 2004a, 2006). In relatively high and convex locations of the Pampean landscape, normally subject to a regime of net hydrological recharge, it is common to find phreatic groundwater of very low salinity suitable for human consumption (Fuschini Mejía 1994).

Figure 4. Evapotranspiration of forest plantations of *Eucalyptus grandis* of different ages and natural grassland in the Concordia region, Entre Ríos (Argentina). Daily evapotranspiration (ET) values correspond to the average of seven dates and were estimated from LANDSAT satellite information. Significant differences between age ranges are indicated with letters.



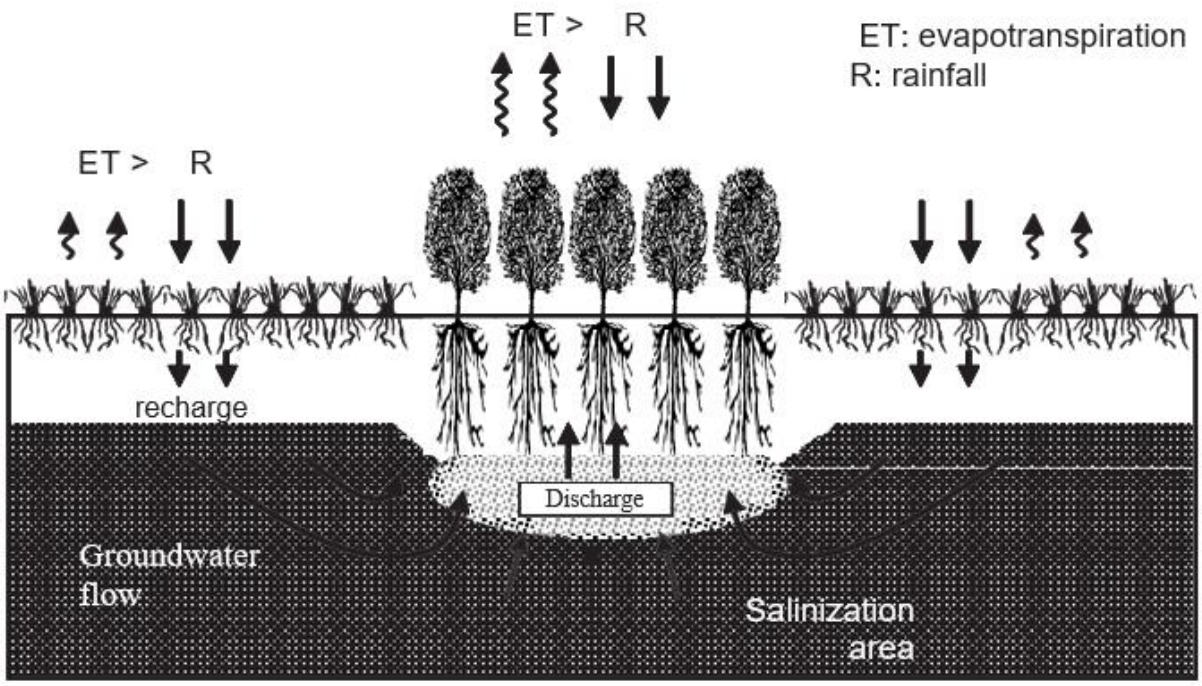
When comparing pairs of natural grassland and forests, 100 to 200 m away from each other, we have found that in this type of topographical situation forest plantations increase the salinity of phreatic groundwater by 3 to 30 times, raising in almost all cases the electrical conductivity of water above the values considered safe for human consumption (Jobbágy & Jackson 2004a, Jackson et al 2005). More detailed analyses of soil moisture profiles and daily and seasonal water table fluctuations (Jobbágy & Jackson 2004a) along with measurements of sap flow in tree trunks (Engel and others, 2005) have made it possible to reconstruct the causes of this salinization process. Forestry absorbs phreatic groundwater (hydrological discharge) and depresses the water table locally. The adjacent grassland areas replenish forestry with the water that they recharge and, in doing so, send salts that remain and accumulate in the place, unlike the water that is evaporated (Fig. 5). As a result of this process, not only does water quality deteriorate, but the soils also become salinized and in most cases become alkaline and sodic below the first 50 cm (Jobbágy & Jackson 2004a). Similar processes have been documented for forest plantations in

Australia (Heuperman 1999), Russia (Sapanov 2000), and Hungary (Nosetto and others, 2006).

For the occurrence of this phenomenon, groundwater must be within reach of the roots of the trees and intermediate sedimentary textures that are not too clayey, preventing the flow of replenishment of the plantation, nor excessively thick, preventing the accumulation of salts by frequent leaching. These conditions would be met in most of the loessic sediments of the Pampas (Jobbágy & Jackson 2004a).

It is appropriate for this section to emphasize that the transpiration differences observed between grassland and forestry would have their ultimate causes in the structural and physiological differences that exist between pastures and trees. Tree-dominated ecosystems often reach deep water reserves to which pastures do not have access (Calder and others, 1993, Canadell and others, 1996), explaining the higher rate of evapotranspiration of forests in dry seasons. At the same time, forest canopies have a greater evaporative capacity than grassland canopies due to their greater roughness and more efficient exchange with the atmosphere (grasslands tend to develop a more effective boundary layer) (Kelliher and others, 1993, Calder 1998,) explaining, in this case, the higher rate of evapotranspiration of forests in wet seasons. These essential differences between forest and herbaceous systems would explain the very strong and generalized hydrological effects observed for a wide variety of tree species in very diverse environments (Jobbágy & Jackson 2004a, Zhang and others, 2001, Farley and others, 2005).

Figure 5. Conceptual model of the effects on groundwater dynamics of an isolated tree plantation in a grassland environment. The plantation receives advective energy input from neighboring grasslands. Together with the higher roughness and greater leaf area of the trees, this results in higher rates of potential evapotranspiration (ET). This, in turn, leads to groundwater consumption and lower recharge levels. Areas where there was net groundwater recharge experience a reversal of hydrological flows after tree planting: there is more water loss, and salts accumulate. This process has been documented in several locations in the Pampean region (Jobbágy & Jackson 2004a).



It is important to recognize that increased water consumption by forestry can be a useful tool in some local circumstances in which the aim is to maintain lower levels in the water tables or reduce the volume of effluent, among others. The control of ascending water tables, a very severe problem in Australia and incipient in some areas of Argentina, could be partially reversed by forestry, although Australian researchers suggest that this could be achieved by covering more than 70% of the watersheds (George and others,1999).

Extraction of calcium and acidity in soils

Just as the higher primary production rates in forestry are inevitably accompanied by increased transpirational water losses, increases in standing plant biomass accumulation generally go hand in hand with increased nutrient sequestration that would otherwise be lodged in the soil (Fig. 2B).

Particularly relevant in this regard is calcium, a scarce element in the tissues of herbaceous plants, especially pastures, but abundant in the tissues of woody angiosperm species (Jobbágy & Jackson 2004b). The beginning of a strong transfer of calcium, like other cations, from the soil to the plant biomass is accompanied by acidity release from the vegetation to the soil, as a necessary balance of charges (Marschner 1995) (Fig 2B). This section explores the magnitude of this process in forested grasslands based on paired forestation vs. grassland experiments around the world, nutrient and proton balances in the Pampa Húmeda, and chemical analyses of water from streams that drain grassland and forested watersheds in Uruguay and Argentina.

Based on the review of published scientific research evaluating the soil changes that accompany the establishment of trees in grasslands, 112 cases were collected, in which possible chemical soil variations were explored in adjacent stands of forests and natural grasslands distributed on five continents on very different soils (Jackson and others, 2005).

A generalized drop in soil pH was found after afforestation (Fig 6). On average, plantations had 0.3 pH units lower than the grasslands at the mineral soil surface (any organic horizon was excluded from the analysis) and the eucalyptus trees generated significantly stronger pH drops than the pines. Along with the effects on pH, forestry reduced the base exchange complex saturation to three-quarters of the original value (from 59% to 45%) from falls in the interchangeable fraction of magnesium, potassium, and calcium. In contrast, the amount of interchangeable sodium increased in 80% of cases and four of them exceeded the 15% saturation threshold, typically associated with the development of physical fertility problems in soils (Jackson and others, 2005, Jobbágy & Jackson 2006).

Using a network of nine eucalyptus plantations and adjacent grasslands in the Pampa Húmeda, we found a general decrease in soil pH. The only exception found was coastal dunes where the high concentration of shell-derived calcium carbonate possibly buffered the acidification process (Jobbágy & Jackson 2003). In three sites studied in greater detail, maximum acidification values were observed at intermediate levels of the soil profile (decreases of up to two pH units between 10 and 50 cm deep) (Fig. 7). The calcium balance in these sites showed no net losses in the ecosystem, but a significant transfer from intermediate areas of the profile towards forest biomass, the organic horizon, and the first centimeters of mineral soil (Jobbágy & Jackson 2003).

Figure 6. Changes in soil pH in forested plots vs. control plots maintained under natural grassland vegetation. The points represent 112 pairs worldwide and the values correspond to the water pH of the mineral soil between its surface and a depth of 10 to 30 cm. Data extracted from Jackson and others, 2005.

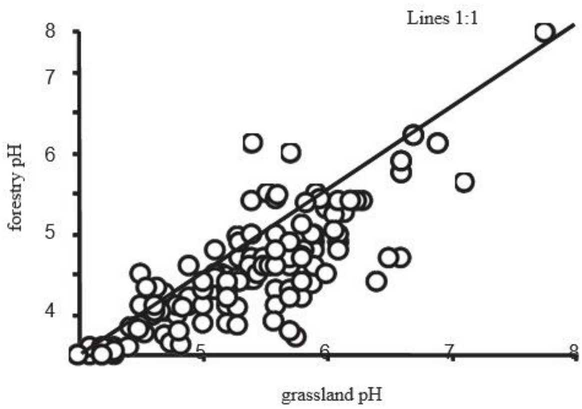
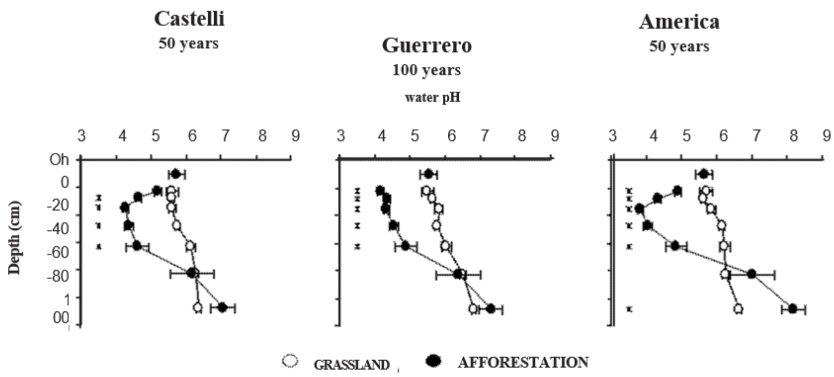


Figure 7. PH profiles in afforested grasslands of Argentina's Pampa Húmeda. The pH (1:1 soil – water, n = 5) was recorded in three pairs of adjacent stands of natural grassland and *Eucalyptus camaldulensis* (plantation age in the header). The asterisks indicate significant differences ($p < 0.05$).



Analysis of acidity changes in soils under plantations from 50 to 100 years of age yielded average proton gain rates of 0.5 to 1.2 kmolc.ha^{-1}. year^{-1}, similar to the values found under severe acid rain conditions in industrial areas of the northern hemisphere (Andews and others,1996). The vertical pattern of acidification and calcium balances point to the vertical redistribution of calcium as the main cause of acidification of soils and do not, however, support the possibility of acidification by the release of organic acids from the canopy or the organic horizon (Jobbágy & Jackson 2003). The latter mechanism, traditionally considered the main cause of acidification, would not be as important in the Pampas and would be even less important under eucalyptus plantations, whose aboveground contributions are more alkaline than the rain (Jobbágy & Jackson 2003). Strong redistribution of manganese was found in the soils towards available forms and towards the surface and arboreal biomass, which is associated with soil acidification and raises questions regarding the availability of nutrients and possible problems of toxicity by metals (Jobbágy & Jackson 2004b). It is important to note that the soil chemical alteration process described here took place under semi-natural conditions in which tree biomass was not harvested. The observed changes can be accentuated and accelerated under typical timber harvesting regimes in commercial plantations and it is worth highlighting that 60% of the calcium in the studied forestations was lodged in the bark of the trees, material that could be left in the harvested plots to limit acidification impacts.

It is also appropriate to consider that forest species differ substantially in their calcium avidity, and some, like many pine species, have much lower requirements than eucalyptus and other angiosperms (Noble and others, 1999).

In the same pairs of afforested and grassland watersheds mentioned in the previous section, we explored the chemical changes in stream waters induced by plantations. In Lavalleja (8 pairs, 4 dates), a decrease in pH was found in all sites and dates (from 0.5 to 1 point). This acidification occurred along with significant decreases in the concentration of cations, mainly calcium, and dissolved inorganic carbon, and with increases in aluminum concentration. In Cordoba (4 pairs, 5 dates), under a drier climate, substantial changes in pH or cation concentration were not detected. So far, these preliminary results suggest that, in Lavalleja, where there are more weathered geological materials and a lower buffer capacity, forestation influence on soils would be transferred to stream water. However, in Cordoba, where the buffer capacity of the geological material may be higher, this would not occur.

Delgado and others (2006,……) show an acidification process in soils of northern Uruguay similar to that observed in the Pampas region. The transport of soluble aluminum from soil to watercourses deserves special attention in forested grasslands given the toxicity of this element and its possible mobilization in case of intense acidification (Jackson and others, 2006, Larssen & Holme 2006).

Our results suggest that soil fertility management in forest plantations in the region will require rethinking the practices and criteria developed so far for herbaceous systems (pastures, grasslands, and annual crops), whose nutrient circulation patterns differ substantially from those of tree-dominated systems. Among other things, it will be necessary to learn to monitor and manage the calcium cycle and to regulate the acidification process of the soils, considering its possible influence on the bioavailability of nutrients and potentially toxic metals, expected in a domain of pH values that is unprecedented in the region.

Looking for alternatives: A mixed ecosystem

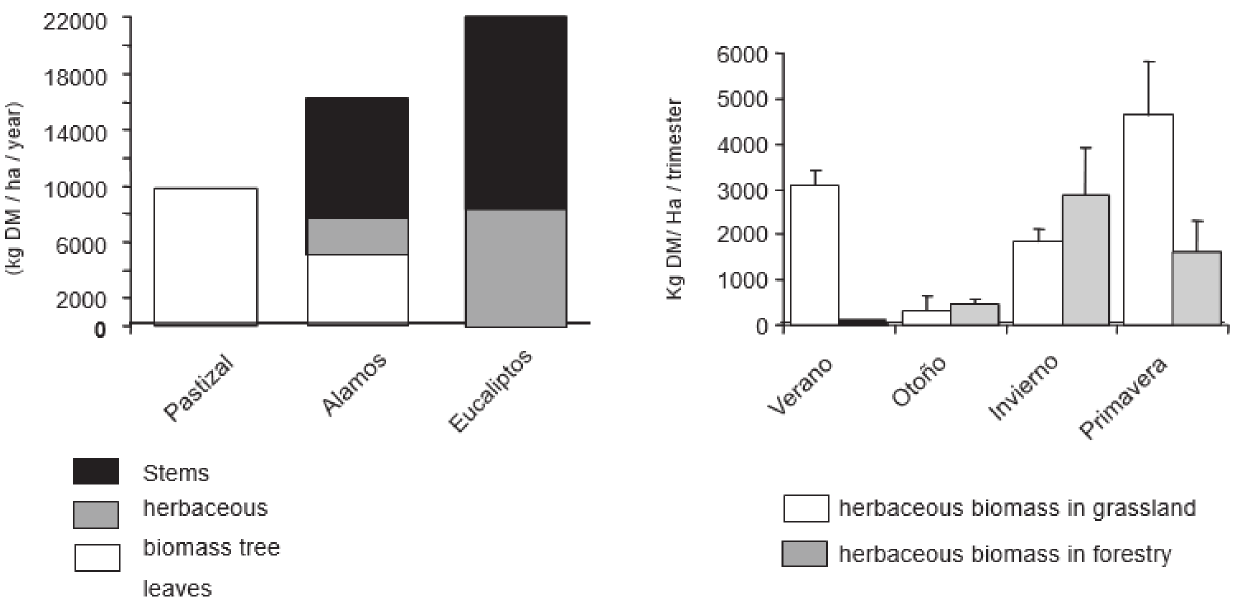
Observing the undergrowth under commercial pine and eucalyptus plantations in Pampean grasslands and comparing them with that of forests of deciduous species such as poplars or acacias quickly notices a consistent difference. While the first ones usually host only a thin bed of fallen leaves and, exceptionally, a scarce cover of minor woody plants and scattered herbaceous plants, the second ones host a community quite similar to a pasture or natural grassland. Behind this contrast lies an interesting opportunity that can be exploited from both forestry and livestock production, while moderating the impacts associated with pine and eucalyptus plantations.

The deciduous tree species share with the evergreen many of the aspects discussed in the previous sections regarding water and calcium consumption, but with the important difference of being active only from six to eight months each year. We have hypothesized that, by leaving a temporary gap in the autumn and winter, which in the climatic conditions of our region can sustain plant growth, the maintenance or establishment of a herbaceous species undergrowth could conserve many grassland components and functions and minimize some of the most worrying hydrological and soil impacts of the plantations. To this end, the effects of forestry with poplars (*Populus deltoides*) on the structure, composition, and primary productivity of natural grasslands in the Pampa Deprimida were evaluated, including the existence and intensity of possible acidification and salinization processes such as those observed in the same type of soils and landscapes when eucalyptus was implanted.

In a network of nine paired sites composed of adjacent stands of non-forested and afforested grassland with poplars of 25 years and densities of 625 to 1100 plants per ha^{-1}, phytosociological surveys and measures of grassland basal coverage were carried out. Although the coverage of live plants was 42% lower in poplars ($p<0.05$), fallen leaves coverage showed an opposite trend, maintaining the proportion of bare soil unchanged after forestry (Clavijo and others, 2005). Afforested stands had a higher proportion of C_3 (winter) species compared to non-afforested ones and few signs of local extinctions or invasions associated with these plantations were found. In two of the sites studied, measurements of seasonal and annual net aboveground primary production of grasslands and poplar forests were made from grass biomass cuttings, collection of fallen material from the canopy of trees in net traps, and measurements of volumetric increase of their stems (Nordenstahl 2005).

Annual net primary aboveground productivity of herbaceous plants was reduced by about half under forestry (Fig. 8A). Poplars, meanwhile, overcompensated for this decline by raising the productivity of the ecosystem as a whole (undergrowth + trees in forestry vs. non-forested grassland) by 60%. Although the levels of total and forest production in these poplar plantations were lower than those reached by red eucalyptus in the same soils (Fig. 8A), these systems generated a forage supply of high strategic value for livestock farming systems of the region, as discussed below. Although the net primary aboveground production of herbaceous canopies under poplar forests was lower than that of grassland in spring and summer, in autumn and especially in winter, this trend reversed (Fig. 8). Grasslands under forests, dominated by winter pastures, produced an average of 3500 kg DM ha^{-1} year^{-1} in autumn-winter, possibly as a result of the indirect benefit that forestry granted to these species by reducing the coverage of summer pastures (Clavijo and others, 2005) and the more direct advantages such as moderation of frost and extreme temperatures under the canopy (Nordenstahl, 2005).

Figure 8. Aboveground net primary production in forests and pastures of the Pampa Deprimida (Castelli – Buenos Aires, Argentina). A. Annual net primary aboveground production for two grassland sites and their respective adjacent poplar stands (*Populus deltoides*, 25 years old)(n=4 in each pair). A third bar corresponding to a *Eucalyptus camaldulensis* (50 years old) plantation located 7 km from the other sites (Jobbágy & Jackson 2003) is added. The fraction corresponding to herbaceous biomass (undergrowth in the case of plantations) measured by repeated harvests on mobile plots, leaves and branches measured from trapped material, and stems measured by volume changes is indicated within each bar. B. Average seasonal aboveground net primary production of herbaceous material for the two grassland stands and their poplar-forested pairs. Bars indicate the standard error (Nordenstahl 2005).



While the evaluation of groundwater and soils in two poplar forests and their adjacent grasslands showed water tables and deep soil salinization, the magnitude of the process was substantially lower than that observed under eucalyptus (Jobbágy & Jackson 2004). Hourly water table level records in one of the pairs of stands showed that, although poplars use water table during the growing season (a process evidenced by nocturnal ascents and diurnal descents of the water table level), during the winter, they generate deep drainage and water table recharge more intensely than pastures, partially compensating the process of salt accumulation (Jobbágy – unpublished data). A pretest of the first 50 cm of soil at two sites showed that poplar plantations maintained the same pH levels as adjacent grasslands, suggesting that the acidification process described for eucalyptus would not take place under this type of forestry or would do so at much slower rates.

In most of the livestock farming systems of the grasslands of Río de la Plata, the winter season has the lowest forage supply, often regulating annual livestock production. Besides production diversification, deciduous forest species plantations in the Pampa Deprimida can host a good source of forage in their undergrowth, capable of complementing that of non-afforested natural grasslands in quality and seasonality.

In non-agricultural environments, such as those usually occupied by commercial forestry, the possibilities for annual green planting or other annual winter forage resources, are limited. Deciduous forestry would continuously maintain a herbaceous undergrowth that, with adequate replanting and fertilization, could substantially improve the efficiency of the livestock farming systems that give space to it, complementing them instead of displacing them (Carámbula & Piñeiro, 2006). The impacts on water and nutrient cycles in these plantations are less intense than that of commercial pine and eucalyptus plantations. Management of their densities and distribution in the appropriate landscape could bring their water and biogeochemical functions closer to those of natural pastures.

This case of "alternative" forestry has been presented with the main purpose of illustrating two central agronomic issues: 1) it is possible to rethink the type of forestry that we implement to minimize the least desired impacts and 2) forestry activity can be integrated with livestock farming, generating synergies in land use. The use of evergreen species such as pines and eucalyptus can be compatible with pastoral systems to the extent that low densities of the order of 400 plants per hectare are implemented. The intermediate shading conditions of these canopies could also favor the production of winter herbaceous plants and temper the effect of frost. The possible models of grassland forestry should be many more and not only the example of poplars in Pampa Deprimida. Public and private technological systems are responsible for exploring and implementing other models.

Other costs and opportunities

This article is focused on the most prominent ecological costs and opportunities from the perspective of matter and energy circulation in ecosystems. Other perspectives on the ecology of forested grasslands reveal new impacts, as is the case of biological diversity. Beyond the potential problems of local extinction of species that could occur in the long term in heavily forested regions, there is a more urgent issue concerning the other side of diversity changes: invasions. Under the canopy of many plantations, plant species historically absent in pastures, are established, and while many can be of little concern from a forest perspective, others become a major problem. Several shrubby or arboreal woody plants of very fast growth have become problematic in various areas of the Río de la Plata grasslands. Some examples are blackberry (*Rubus fruticosus*), ligustrum (*Ligustrum sp.*), and black acacia (*Gleditsia triacanthos*.) These compete with forest trees and make it very difficult to access and work in plantations, not to mention the exploitation potential for livestock farming in the undergrowth. In many cases, the forests act as a starting point for these exotic species to advance over the adjacent pastures. In general, these are species dispersed by birds that arrive in large numbers to the forests, where the birds nest or spend a good part of the time and find there an appropriate environment to grow and reproduce. The problem requires careful management of the undergrowth and can be based on grazing as a control tool (Clavijo and others, 2005).

Another problem is fire, a common disturbance in grasslands. Often used as a management tool by livestock farmers, fire becomes one of the main threats to forest producers. Burned grassland areas often suffer surface damage, experiencing relatively low temperatures that do not completely eliminate vegetation cover and do not affect organic carbon reservoirs in the soil. On the other hand, forests offer a quantity of fuel that allows relatively high-temperature levels to be reached, and this, added to the lack of a fire-resistant undergrowth, multiplies the chances of soil erosion and ecosystem damage after a fire. In forested areas of the Cordoba ranges we detected soil losses of up to 0.5 m due to water erosion after a severe fire, something rarely observed in grasslands. Moreover, the potential effect of combustion over the soil organic matter is added, sending into the atmosphere not only the carbon sequestered by the plantation but also the one fixed by the previous pasture.

The risk arises from the coexistence of fire and forestry. This risk requires a careful approach when choosing land for forestry and designing prevention and contingency plans that contemplate the natural and anthropic frequency of fire in local livestock systems (Di Bella and others, 2006). It is interesting to highlight that the negative impacts of exotic species invasions and fire can be minimized with proper management in silvopastoral systems.

Conclusions

Since the arrival of the first Europeans to the vast grasslands of the Río de la Plata, trees have been one of their most ubiquitous partners, providing shadow, firewood and protection from the winds. In the last few decades, the myriad of ancient isolated shelter forests has led to larger commercial plantations and more efficient production and use in different spots of the region. The great productive potential of these plantations is linked to profound functional changes in ecosystems, some of which can affect the provision of key ecological services such as the provision of water or the maintenance of soil fertility (Paruelo and others, 2006, ...). From bibliographic reviews and data generated by our group we can affirm that forest plantations of pines and eucalyptus trees produce the following changes in ecosystems:

1- Primary productivity (carbon gain or growth rate) and biomass accumulation are higher in forest plantations than in the natural field. Forestry impacts on carbon accumulation in soil organic matter are still uncertain.

2- Higher productivity is accompanied by increased water use by trees, increasing the amount of evapotranspirated water and decreasing hydrological yield. Decreases in runoff flow would be close to 50% while evidence is still uncertain about aquifer recharge.

3- Forest plantations acidify the soil and water of the streams of the watersheds they occupy, mainly due to a high accumulation of cations (calcium and magnesium mainly) in the tree biomass. The magnitude of the impact of these changes on the accumulation of (toxic) aluminum in soil and water is still uncertain, but deserves attention.

4- In situations where groundwater is close to the surface, trees can take advantage of it and salinize soils and water tables. This phenomenon would be observed in areas with sediments of medium textures (e.g., loessic materials) but not in areas of dunes or very clayey sediments.

5- It is urgent to generate information about the impacts of forestry on biodiversity (especially on the dynamics of invasive species) and their influence on the recurrence, intensity and extent of fires, as well as the effects of forest fires on soil erosion and fertility.

6- Forestry with deciduous species could complement existing livestock farming systems, minimizing the associated environmental impacts.

As long as societies recognize, in an integral way, the services and goods that the different land uses offer and the commitments that exist between them, they will be able to explicitly raise and discuss the costs and benefits that accompany the transformation of agricultural systems (Paruelo and others, 2006,........).. In the case of the advance of forest plantations on the Río de la Plata grasslands, some of these commitments are already visible and their recognition allows taking the first step towards new regulatory frameworks and forest systems that optimize the production of goods of commercial value and the provision of ecosystem services in a sustainable way. For this, it is necessary to combine what we currently know, in our country and others about forests established on grasslands, with innovative and bold approaches that understand and take advantage of local conditions.

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