Quantifying the Hydrologic Impacts of Afforestation in Uruguay: A Paired Watershed Study

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Substantial portions of grassland are being converted to managed forestland in Uruguay. Long-term paired watershed studies in other continents indicate that water yields from managed forestlands will be reduced compared to water yields from grasslands. Very few long-term paired watershed studies to quantify changes in water yields due to afforestation have been conducted in South America. This study was initiated in 1999 to determine the hydrologic impacts of changing land use from grassland to pine plantation in Uruguay. Two adjacent watersheds (~100 ha) located in the Tacuarembó River basin were selected for the paired watershed study. Outflow rates were continuously measured on each watershed. Rainfall and meteorological conditions were also measured continuously on the site. During the initial pretreatment period (July 01, 2000 through June 2003) both watersheds were in pasture. In July 2003, one watershed (LC-PINE) was planted with loblolly pine, while the other (LC-PAST) remained in pasture. Data collection has continued through 2008. Reductions in annual water yields from the pine plantation have ranged from no reduction in the third year to a 28% reduction in the fourth year since tree planting. The year with the greatest yield reduction was characterized by a very dry period followed by a very wet period. The water yield reduction over the last three years of the study has been 15%. Distributions of outflow rates with time have also changed since tree planting. Peak flow rates from LC-PINE were reduced on average by 50% two years after planting and by 75% four years after planting. Times to peak flow rate at LC-PINE increased on average by 11 minutes two years after planting and by 26 minutes four years after planting. The Richards-Baker flashiness index was calculated using a six minute time step to determine the flashiness of both watersheds. The flashiness index for the LC-PINE watershed relative to the LC-PAST watershed was on average 50% lower during the fourth year after planting than during the pretreatment period. Flow duration curves for six minute intervals also show reduction in high flow rates from the LC-PINE watershed relative to the LC-PAST watershed. Baseflow rates from the forested watershed have not changed since planting. This study will continue through the pine growth cycle which will include pruning, thinning and harvest management practices typically used in the region.

Introduction

Uruguay is located in the eastern part of South America between latitudes 30° and 35° South. It is in a zone of humid subtropical to temperate climate. The country is characterized ecologically by native grasslands (savannah) and topographically by plains and rolling hills with elevations up to 500 m. About 85% of Uruguay's land mass (176,000 km^2) is in agriculture, the highest percentage in the world. Historically, most of the grasslands have been used for livestock grazing while some of the better soils have been used for row crop farming.

In an effort to diversify the rural economy, the Uruguayan government instituted financial incentives for tree production in 1989. In response, national and multinational timber corporations have purchased land and planted trees (primarily eucalyptus, loblolly pine, and slash pine) over significant portions of the landscape. Approximately 800,000 ha of grasslands were planted to trees between 1990 and 2007. Due to the magnitude of these land use changes, local stakeholders have expressed concerns regarding the impact of converting grasslands to tree plantations on water resources. Of particular concern are the effects of the tree plantations on water yield and downstream water supply, as well as the impact on base flows in the receiving streams and rivers.

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Numerous paired watershed studies on afforestation and deforestation have been conducted in Australia, New Zealand, South Africa, Great Britain, and the US. Reviews of these studies have concluded that rainwater yield from the landscapes with established trees is less than from landscapes with shorter vegetation (Bosch and Hewlett, 1982; Sahin and Hall, 1996; Brown *et al.*, 2005, and Farley *et al.*, 2005). The reduction in water yield has been attributed to the greater evapotranspiration (ET) from trees as compared to shorter vegetation. Holmes and Sinclair (1986) and Zhang *et al.* (2001) developed relationships between annual ET and annual rainfall for various types of vegetation including grass and trees. These relationships are widely used to estimate the impact of afforestation on annual water yield; however, these relationships do not consider other factors that can affect water yield such as soil water capacity, soil infiltration properties, and plantation management (Van Dijk and Keenan, 2007). These relationships also do not account for effects of afforestation on seasonal, monthly, and daily flows which may have more important impacts on water resources than mean annual yields (Brown *et al.* 2005).

Long-term paired watershed studies on effects of afforestation have not been conducted in Uruguay and surrounding areas; however, Silvera *et al.* (2008) compared flow events from the 2100 km^2 Manuel Diaz basin in Uuguay before and after afforestation (25% of the watershed area). They observed 59 to 65% reductions in peak flow rates and a 33 to 43% reduction in event flow volumes. Silvera *et al.* (2008) also estimated decreases in annual streamflow between 8.2 to 36.5% after afforestation.

In the fall of 1999, researchers at North Carolina State University, in cooperation with the Instituto Nacional de Investigación Agropecuaria (INIA) and Weyerhaeuser Company initiated a study to evaluate the long-term impacts of land use conversion from grassland to pine plantation on the hydrologic regime and water quality. The field study employed a long term paired watershed approach to evaluate the effects of afforestation. Two watersheds were monitored for a three-year pretreatment period during which the land use in both the control and treatment watersheds was grassland with livestock grazing. The treatment watershed was subsequently planted with loblolly pine (Pinus taeda L.) in July 2003, and both watersheds have been continuously monitored to date and monitoring will continue through tree maturation and harvesting. This paper presents the hydrology of the watersheds during the pretreatment period and for the first 5 years of the treatment period.

Materials and methods

A paired watershed approach was used to determine the effects of afforestation on hydrology. Two small adjacent watersheds (69 and 108 ha in size) were selected for study in the Tacuarembó river basin (Figure 1). The watersheds are located on the La Corona estancia of the El Cerro tract owned and managed by Weyerhaeuser Uruguay Both of the watersheds were instrumented to continuously measure precipitation, outflow rates, weather parameters, and water table elevations. Both watersheds were monitored in a grazed pasture land-use for a three year pre-treatment period (July 2000 through June 2003) before planting the pine. Relationships for water yield, peak flow rates, and base flows between watersheds were determined to establish the hydrology of the two watersheds before trees were planted.

The treatment watershed (LC-Pine, 108 ha) was planted with pine seedlings in July 2003. The control watershed (LC-Past, 69 ha) remained in pasture with livestock grazing. The same relationships have been determined for the two watersheds for the five year treatment period after planting and compared to the pre-treatment period.

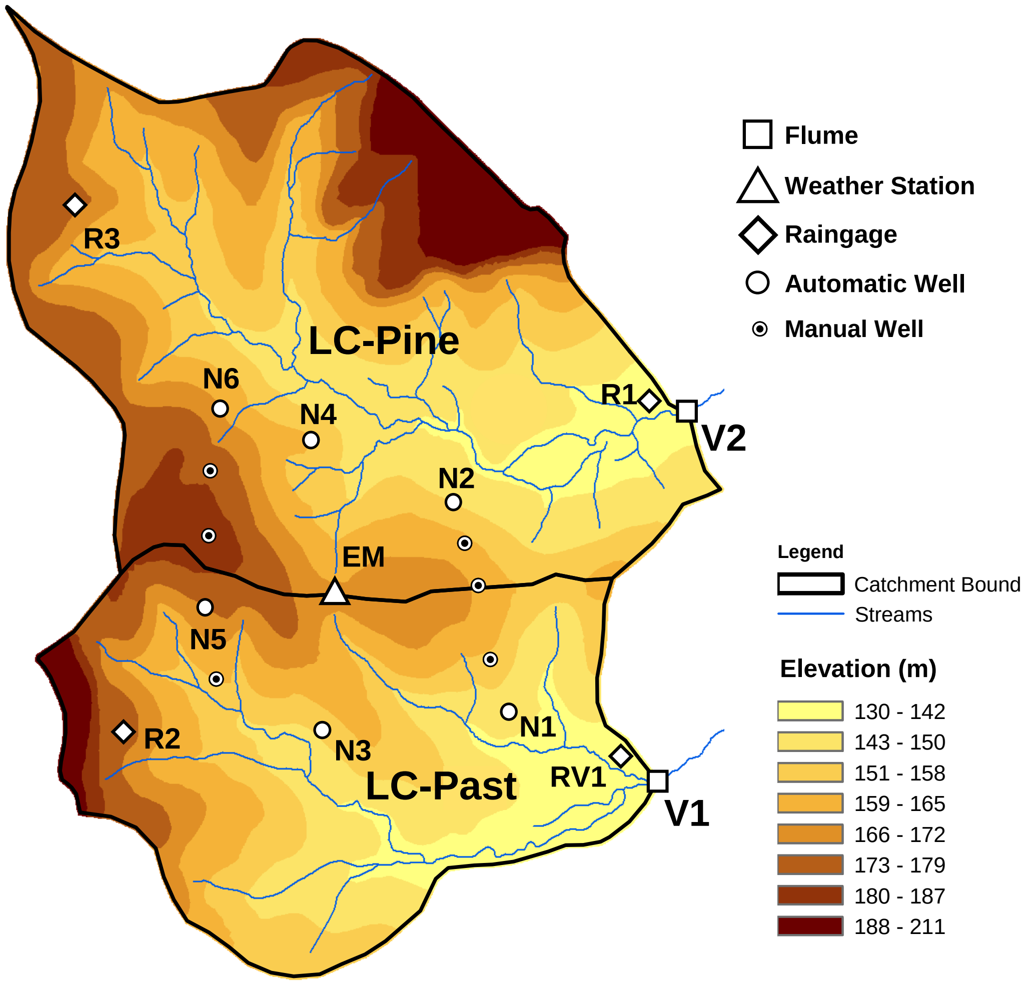

Figure 1. Location of instrumentation on watersheds: raingages, weather station, ground water wells and flumes. Topography and hydrography of watersheds are also shown.

Site Description

The topography of the watersheds is characterized by a rolling landscape with protruding rocky hillocks of basalt and sandstone. The elevation of LC-PAST varies from 130 to 204 m, while LC-PINE varies from 136 to 192 m (Figure 1). The topographic relief of the site shows an upper elevation plateau and cliff area in the northern portion of watershed LC-PINE and a similar smaller feature in the western portion of watershed LC-PAST. Land slopes mostly ranged from 2 to 15%, except in the cliff areas. The aspect of watershed LC-PAST is primarily to the east, while watershed LC-PINE faces south and east.

The hydrography of the watersheds is characterized by an extensive network of incised channels that convey the surface and subsurface flows from the landscape to the outlets of the watersheds. Slopes of the stream channels range between 4% and 10% in the tributaries in the upper elevations of the watersheds and between 1% and 1.5% in the main channels in the lower portion.

The soils on the watersheds in the lower and middle elevations are dominated by sandy loam and sandy clay loam material ranging in depth from 0.8 to 1.7 m over sandstone. The higher elevations are outcroppings of basalt and sandstone overlain by a shallow topsoil layer ranging in depth from 0.10 to 0.35 m. Watershed LC-PINE has a higher proportion (27%) of the shallow soils than LC-PAST (8%).

The two watersheds were managed as grassland with livestock grazing during the three-year pretreatment period (July 2000 through June 2003). Grazing density for the period was estimated by field personnel to be

0.9 cattle units per hectare. One cattle unit is defined as the foraging needs of one cow of 380 kg weight with calf. The treatment watershed (LC-PINE) was planted with loblolly pine seedlings (Pinus taeda L.) in July 2003, while the control watershed (LC-PAST) remained grassland with livestock grazing. Riparian corridors, equipment access lanes, and cliff faces were not planted, resulting in 57% afforestation of LC-PINE. The trees were planted in furrows (approx. 10 cm deep and 70 cm wide) and spaced approximately 2.5 m apart. Planting density was 1,000 trees per ha, per the standard planting practices of Weyerhaeuser Uruguay. The area between furrows was left with grass vegetation, and the furrows were aligned perpendicular to the hillslopes. Livestock were not allowed to graze on the treatment watershed for the first five years after tree planting.

The general climate for most of Uruguay, including the research site, is mid-latitude humid subtropical grassland (Cfa) according to the Köppen climate classification system. The humid subtropical climate has hot, humid summers with frequent thunderstorms and mild winters with precipitation resulting from mid-latitude cyclones. Average annual rainfall measured at a weather station operated and maintained by INIA in the town of Tacuarembó (35 km south of the research site) was 1,483 mm for the 26-year period from 1979 through 2004. Rainfall varied from as low as 841 mm in 2004 to as high as 2,797 mm in 2002. Rainfall is uniformly distributed throughout the year, with slightly less rainfall in the months of June, July, and August than in other months. The estimated average annual potential evapotranspiration (PET) using corrected pan evaporation data from the INIA station was 1,262 mm.

Field Measurements

The instrumentation on the project site included a weather station, an automatic rain gauge, four manual rain gauges, flow stage recorders at two outlet flumes, and six water table elevation recorders (Figure 1). The watersheds have been continuously monitored from the beginning of July 2000 through April 2009.

A 3-meter tall Campbell Scientific weather station equipped with automatic sensors and a CR10X data-logger was installed on the ridge between the two watersheds (Figure 1). The sensors continuously measure air temperature, soil temperature, relative humidity, wind speed, wind direction, solar radiation, and net radiation on a 30-second interval and store data on a 15-minute basis for analysis. The weather station is also equipped with an automatic rain gauge. The 15-minute data are summed or averaged to obtain daily values

Rainfall is being continuously measured using two automatic tipping bucket rain gauges. One of them (R1) is located near the flume outlet of watershed LC-PINE, and the other is connected to the Campbell Scientific weather station (EM) (Figure 1). The time of each tip of the tipping bucket (representing 0.254 mm of rain) at the R1 gage is recorded by Onset (HOBO) data-logger. Rain data at both locations are also backed up by two manual rain gauges. Four additional manual gauges (RV1, R2, R3, and R4) were installed across the two watersheds to study the variability of rain during storms (Figure 1). Rain gauge R4 is located at the ranch house just south of watershed LC-PAST.

Flow rates at the outlet of the two experimental watersheds were measured using 1.37 m high HL flumes (Amatya *et al.*, 2001). These concrete flumes with stainless steel measuring sections were designed using the guidelines provided by Bos (1989). A Stevens Type F recorder with a float and weight system located in the stilling well of the flume entry measures the fluctuation of water levels during the events. A potentiometer is located on the recorder gears and was set to record the stage elevations through a data logger. Stage values were recorded every 3 minutes until September 2002 when an ISCO 720 flow probe was installed that recorded stage every 2 minutes. A calibrated rating curve provided by Bos (1989) was used to calculate flow rates through the flume outlet from measured flow stages. If stage elevations exceeded 1.37 m, flow rates were calculated assuming a broad crested weir located at the top of the HL flume. Emergency spillways with broad crested weirs and separate stage recorders were installed in April 2004 to more accurately measure high flow rates during large flow events.

Data Analysis

Rain data from gauge (R1) is used for our analyses since the break point data better describes rainfall intensity. Missing and/or bad data are supplemented using data from the weather station (EM). The daily weather data were used in the Penman-Monteith method for estimating reference evapotranspiration or PET for a grass reference (Jensen *et al.*, 1990).

Regression analyses were used on the monthly outflow volumes to determine relationships between the watersheds during the pretreatment period. An asymmetric wave trend was observed in the residual plots of the linear regression model, so a nonlinear model was developed using the equation:

$$y = mx + b - (m-1)e^{-kx} \tag{1}$$

where: y=monthly flow from LC-PINE (mm), x=monthly flow from LC-PAST (mm), m, b, and k are coefficients.

Expected monthly flows from the LC-PINE watershed during the treatment period were predicted with the resulting model using the measured flows from the control (LC-PAST). Differences between the expected and the observed flows were computed. Confidence intervals (95%) were calculated for individual values to test the significance of each monthly value predicted for the treatment watershed during the treatment period. Expected annual flows from LC-PINE were calculated by summing the predicted monthly values for each year. Linear and non-linear regression analyses were conducted using PROC REG and PROC NLIN procedures in SAS v9.1.

Characteristics of storm hydrographs were evaluated for numerous storms during three separate periods of the study. The periods were before planting (January to June 2001), 1.5 to 2 years after planting (January to June 2005), and 3.5 to 4 years after planting (January to June 2007). Time to peak (TP) was defined as the time from the beginning of rainfall to the peak flow rate of the hydrograph. The peak flow rate (QP) was the greatest flow rate observed during the runoff event and the total storm flow (TQ) was the cumulative flow volume from the beginning of the event until the flow rate fell below 0.006 mm/hr. The time periods in 2005 and 2007 were selected because rainfalls during these periods were similar to those observed during the treatment period.

The differences between the times to peak at the watersheds (TP for LC-PINE minus TP for LC-PAST) were used to compare storm hydrographs in 2001 to those in 2005 and 2007. The ratios of peak flow rates (QP for LC-PINE divided by QP for LC-PAST) were used to compare peak flow rates of storm hydrographs in 2001 to those in 2005 and 2007. The ratios of total storm flow (TQ for LC-PINE divided by TQ for LC-PAST) were used to compare total flow of storms in 2001 to those in 2005 and 2007.

A flashiness index developed by Baker *et al.* (2004) was used to calculate the flashiness of the streams in both watersheds. The Richards-Baker flashiness index is expressed as:

$$FI = \sum_{t=1}^{n} |q_t - q_{t-1}| \Big/ \sum_{t=1}^{n} q_t \tag{2}$$

Where: FI = Flashiness index, t = time, and q = flow for time period t

The Richards-Baker flashiness index was developed for large streams and used a daily time steps. A daily time step was too large to capture the flashiness of flow from the small watersheds at La Corona; therefore, a much smaller time step was selected for this analysis. Since flow rates were recorded at three minute intervals from 2000 until 2002 and at two minute intervals after 2002, we used a six minute time step to compute the flashiness index. Flashiness indices were calculated for each six month period (January through June) for the years, 2001, 2003, 2005, and 2007.

Results and Discussion

Weather and Rainfall

Weather conditions during the pretreatment period were much wetter than during the treatment period (Table 1). Annual rainfall for all three years (July 2000 through June 2003) of the pretreatment period was at least 310 mm greater than the 26 year average (1483 mm/yr). Annual rainfall of 2071 mm in the second year was the wettest year in the previous 22 years and the total rainfall amount of 2539 mm in the third year greatly exceeded that of the second year.

Rainfall during the treatment period (July 2003 through June 2008) was much lower than during the pretreatment period (Table 1). Annual rainfall amounts for all five years of the treatment period were below average. Total rainfall of 1049 mm in the first year was less than the third driest (1122 mm) in the previous 22 years, and the 975 mm in the third year was between the driest (895 mm) and the second driest (1029 mm) in the previous 22 years. Rainfall for the fifth year was very similar to that of the third year (977 mm). Rainfall amounts for the second and fourth year were near average. They were only 89 mm and 70 mm below average, respectively. For the eight year study period we have observed three wet years, three dry years, and two average years for an eight year average of 1529 mm.

Average annual PET calculated by the Penman-Monteith method using the weather values recorded at the research site (1347 mm) was greater than the 20 year average annual corrected pan ET (1262 mm) collected from a weather station in Tacuarembó . The 3 year annual average Penman-Monteith PET for the pretreatment period (1300 mm) was lower than the 5 year annual average Penman-Monteith PET for the treatment period (1374 mm). Annual PET during the pretreatment period ranged from 1254 mm in the second year to 1379 mm in the first year (Table 1). The highest annual PET during the treatment period was 1466 mm for the second year while the lowest annual PET was 1275 mm for the fourth year.

All three years in the pre-treatment period had large water surpluses. Rainfall exceeded PET by 437 mm, 817 mm, and 1270 mm for years 1, 2, and 3 respectively (Table 1). Potential water deficit conditions occurred with PET exceeding rainfall for four of the five years of the treatment period.

Table 1. Annual rain, PET, potential deficit (rain – PET) observed for each year of the study. Measured flows for the Pasture site and Pine site are also shown along with the expected calculated by the relationship developed during the pretreatment period.

	Rain	PET	Rain-PET	Measured Flow LC-PAST	Measured Flow LC-PINE	Expected Flow LC-PINE *	Percent of Expected Flow **
Pretreatment							
Jul 00-Jun 01	1808	1379	429	798	1068	1032	103
Jul 01-Jun 02	2071	1254	817	1019	1198	1243	96
Jul 02-Jun 03	2539	1269	1270	1321	1599	1586	101
Treatment							
Jul 03-Jun 04	1049	1392	-341	150	253	301	84
Jul 04-Jun 05	1395	1466	-71	383	480	540	89
Jul 05-Jun 06	976	1411	-436	160	265	257	103
Jul 06-Jun 07	1414	1275	139	303	340	474	72
Jul 07-Jun 08	977	1332	-355	137	217	235	92

*Expected flow was calculated using the nonlinear relationship for monthly values shown in Figure 2 and summing the expected monthly values for each year.

Water Yield

Outflows from both watersheds reflect the weather conditions of the study period. Average annual outflow was high (1046 mm for LC-PAST and 1288 mm for LC-PINE) during the pretreatment period and much lower (249 mm LC-PAST and 335 mm for LC-PINE) during the treatment period (Table 1). The differences in hydrology between the pretreatment and treatment periods made determining the impact of the tree planting more challenging, especially during the first years after planting when impacts were expected to be small.

Outflow from the treatment watershed (LC-PINE) was consistently greater than from the control watershed (LC-PAST) during the pretreatment period. The differences were mainly due to a higher baseflow at LC-PINE than at LC-PAST. Possible causes for higher baseflow are lower ET from the LC-PINE watershed or an inflow of groundwater from outside of the watershed. One notable difference between the watersheds is the higher percentage of shallow soils on LC-PINE (27%) compared to LC-PAST (8%). One hypothesis is that less water is stored in the shallow soils and, consequently, less water is available for ET. The excess water moves to the groundwater and is available for base flow. This hypothesis and the hypothesis that groundwater was entering the watershed from offsite were tested in a SWAT modeling study of the watersheds (von Stackelberg 2007). Daily outflows predicted by the SWAT model for both of the scenarios fit the measured outflows very well. We have not found evidence to confirm that groundwater is entering LC-PINE from off site. We have, however, observed that tree growth in the shallow soils is much less than growth on the deeper soils. This is a good indication that ET is lower from these shallow soils.

Despite the flow differences between LC-PAST and LC-PINE, we were able to develop good relationships (Figure 2) between the watersheds for monthly flow during the pretreatment period. The relationship appeared linear when flow rates were greater 60 mm (Figure 2a); however, the relationship became nonlinear as flows decreased from 60 mm (Figure 2b). A nonlinear model was created by subtracting an exponential term from the linear model which caused the slope of the relationship to increase in the low flow range. The better fit of the model to the data in the lower range was an important improvement since most of the flows during the treatment period were in the low flow range. The linear model would have over predicted flow from the treatment watershed for these conditions

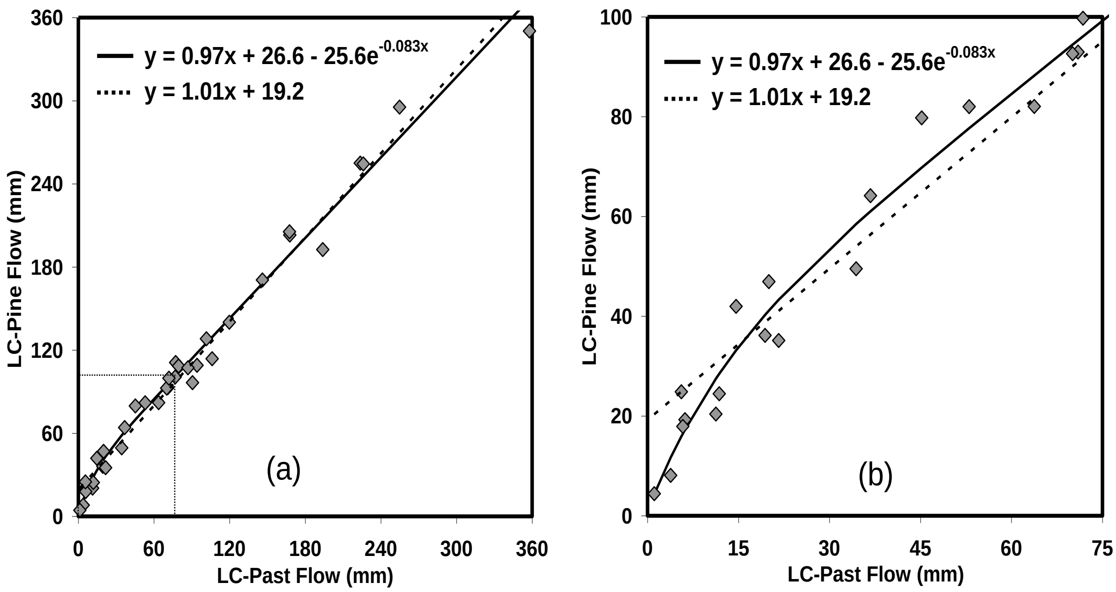

Figure 2a. Plots of the relationship between watersheds LC-PINE and LC-PAST for monthly flow during the pretreatment period (2000-03). Linear and non-linear regression models are shown. Figure 2b. shows details of the models in the lower flow ranges

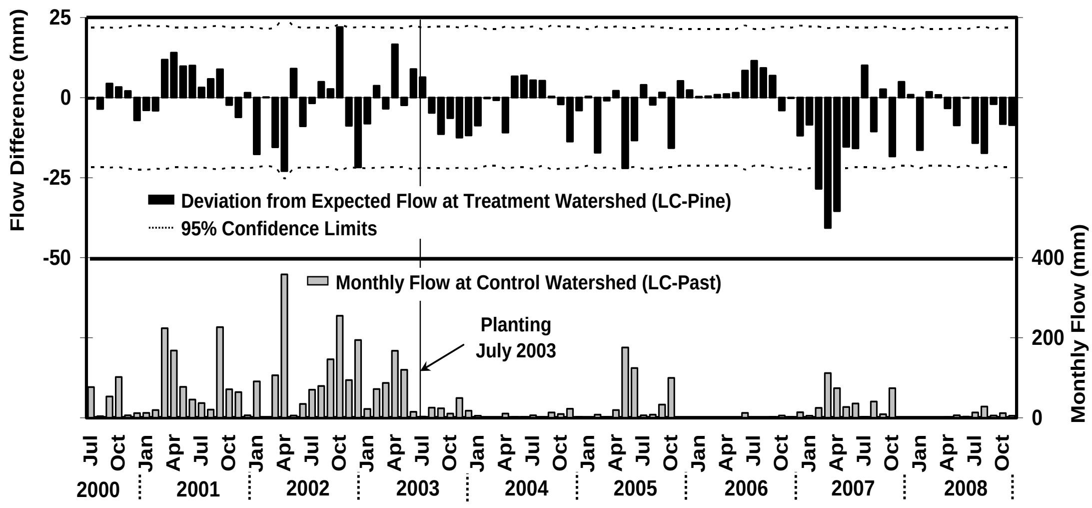

Figure 3. Monthly deviations of measured outflows from expected outflows for the treatment watershed (LC-PINE) during the pretreatment and treatment periods. Expected outflows and 95% confidence limits were calculated by the non-linear model. Measured monthly flow from the control watershed (LC-PAST) is also shown.

The hydrologic impacts of planting trees on sloping grasslands are likely caused by two sets of factors: factors affecting actual ET and factors affecting infiltration. The deeper rooting depth of trees allow them to draw water from a deeper soil profile which results in the trees being able to access more water during dry periods than shallow rooted grass. This would result in higher ET from the forested watershed. Evidence of increases in ET would be observed in reductions of water yield that occur in monthly outflow relationships between the forested watershed (LC-PINE) and the grassed watershed (LC-PAST).

Consistent differences between the two watersheds in monthly outflow were not clearly evident in the first three years after planting (Figure 3). Clear evidence of changes in monthly outflow first occurred in the late summer and fall of 2007 during a period of high rainfall that occurred after a long dry period. Rainfall for the period from December, 2006 through April 2007 was 238 mm above average. This wet period was preceded by a 13 month dry period when rainfall was 834 mm below average. Flows from the treatment watershed were below the expected outflows predicted by the model from December 2006 to June 2007. The monthly deviations of measured outflows from expected outflows for were below the lower 95% confidence limit for February, March, and April, 2007 (Figure 3). While the flow reductions at the treatment watershed occurred during this period, the increase in water use at the treatment watershed likely occurred during the preceding dry period when the deep rooted trees transpired more water from the soil than did the grass. Flow reductions occurred during the wet period when much of the rainfall went to replenishing the soil at the treatment watershed rather than to outflow.

After the soil water was replenished, the monthly outflow volumes were near the expected outflow volumes predicted by the model (Figure 3). Deviations of measured outflows from expected outflows were within the 95% confidence limits for each month from May 2007 through December 2008.

Changes in annual water yields due to pine plantations were calculated by summing the measured monthly flows from LC-PINE for each year and comparing those values to the summations of the expected monthly flows. Changes in annual yields ranged from a 3% increase in the third year to a 28% reduction in the fourth year after tree planting (Table 1). The year with the greatest yield reduction was the year characterized by the very dry period followed by a very wet period. A 16% yield reduction was calculated for the first year after planting. A reduction of this magnitude was not expected since the trees were very small during the first year. The first year after planting was much drier than the three previous pretreatment years. Using the model developed in the wet years may result in errors in predicting the expected flows during the dry years. The cumulative water yield reduction for the last three years has been 15%.

Table 2. Comparison of times to peak (TP), peak flow rates (QP), and total storm flows (TQ) for storm hydrographs observed before and after planting of loblolly pine on watershed D2.

	Time to Peak TP_{PINE}-TP_{PAST} mm:ss	Peak Flow Rates QP_{PINE}/QP_{PAST}	Total Storm Flow TQ_{PINE}/TQ_{PAST}
2001 Mean N=20	9:09 a	1.52 a	1.56 ab
Stdev	11:07	1.00	0.62
2005 Mean N=12	26:20 bc	0.75 b	1.21 ab
Stdev	11:48	0.35	0.43
2007 Mean N=18	35:16 bc	0.39 c	0.69 c
Stdev	18:07	0.17	0.17

Means followed by different letters are significantly different from each other at P<0.05 – Student's t-Test

Reductions in monthly water yields will likely vary from season to season and from wet periods to dry periods. These monthly variations will result in year-to-year variations as well. A better understanding of these patterns will lead to more effective management of water resources.

Flow Distribution

While afforestation increases ET which results in water yield reductions, afforestation likely increases the amount of water infiltrating into the soil as well. Increases in infiltration could be caused by three factors after the trees were planted. One factor is that the land was no longer being grazed which reduces soil compaction by livestock and allows the grass to grow taller and slow surface runoff from the land. Another possible factor is that the trees were planted in furrows perpendicular to the land slope, which would increase the effective surface storage and increase infiltration. A third possible factor is that the activity of the larger tree root system over time may create more porous surface soils. While increases in infiltration can affect water yield, the more evident impact of changes in infiltration will be on the distribution outflow rates over time.

Changes in the distribution of outflow rates over time as seen in storm hydrographs were observed between the pretreatment period and the treatment periods. Peak flow rates from the treatment watershed (LC-PINE) were reduced and flow durations were increased during the treatment periods (Table 2). Peak flow rates from LC-PINE were on average 1.5 times greater than those at LC-PAST during the pretreatment period. Peak flow rates from LC-PINE were on average only 75% of those from LC-PAST during the period in 2005, and only 39% of those from LC-PAST during the period in 2007. During the pretreatment period the peak flow rates from LC-PINE occurred on average 9 minutes later than peak flow rates from LC-PAST. Peak flow rates from LC-PINE occurred on average 20 minutes later than that from LC-PAST during the period in 2005. Peak flow rates from LC-PINE were 35 minutes later than the peak flow rates from LC-PAST during the period in 2007. Total storm flow volumes from LC-PINE were 1.6 times greater than at LC-PAST during the pretreatment period, but where only 69% of LC-PAST storm volumes late in the treatment period.

The flashiness indices for the control (LC-PAST) watershed were always greater than those for the treatment (LC-PINE) watershed (Table 3). This would be expected since LC-PAST is smaller in area than LC-PINE and LC-PINE has higher baseflow. In general, the flashiness indices for LC-PAST for each six month period increased with time, while the flashiness indices for LC-PINE for each six month period decreased with time. Changes in flashiness indices would not be expected during the pretreatment period since both watersheds were in pasture for that period; however, we observed that both watersheds were more lightly grazed and had taller grass during the early part of the pretreatment period. This would explain the increase in flashiness indices on LC-PAST from 2001 to 2003, but a similar increase would be expected on the LC-PINE watershed. A small decrease in the six month flashiness indices from 0.086 for 2001 to 0.081 for 2003 was observed at LC-PINE. The greatest change in the flashiness indices at LC-PINE occurred after the trees were planted when the six month index decreased from 0.081 in 2003 to 0.064 in 2005. The flashiness index for the LC-PAST watershed was only 1.2 times greater than that of the LC-PINE watershed at the beginning of the study. For the seventh year (2007) of the study, the flashiness index for the LC-PAST watershed was 3 times greater than that of the LC-PINE watershed.

Changes in flow distributions resulting from afforestation were also evident in comparisons of flow duration curves for time periods before and after tree planting (Figure 4). While the flow duration curves for

2001 and 2007 were similar for LC-PAST, the general slope of the flow duration curve for 2007 at LC-PINE was much less than the curve at LC-PINE for 2001. For both years, flows were greater from LC-PINE than from LC-PAST for more than 90% of the time. This reflects the higher base flows at LC-PINE. Flows from LC-PAST were greater than from LC-PINE

Table 3. Flashiness indices calculated for 4 six month periods at the watersheds. Two of the periods were before planting of loblolly pine on watershed LC-PINE in July 2003 and two periods were after planting.

	Flashiness Index LC-Past	Flashiness Index LC-Pine	LC-Past / LC-Pine
Jan-Jun-01	0.105	0.086	1.22
Jan-Jun-03	0.132	0.081	1.63
Jan-Jun-05	0.152	0.064	2.38
Jan-Jun-07	0.173	0.058	3.00

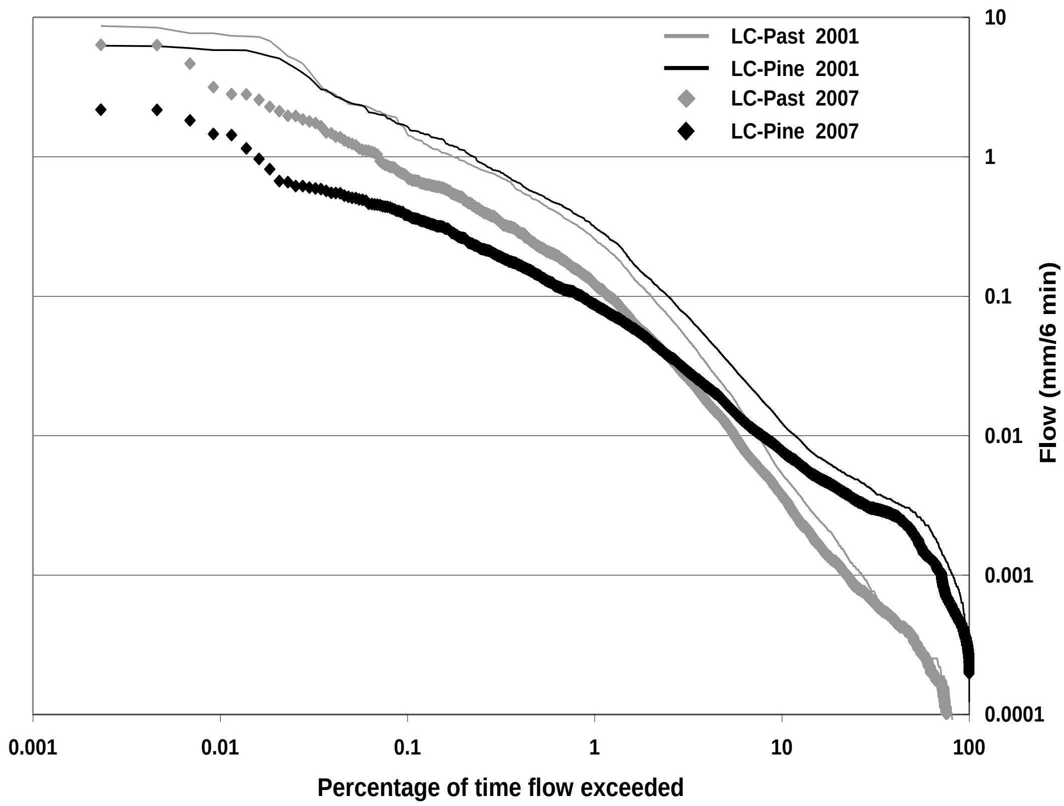

Figure 4. Flow duration curves from January through June of 2001 (before planting) and 2007 (after planting). Flow data points used in these curves were collected every six minutes.

during the very high flow events for both years. The most profound difference between the flow duration curves for the two years is that flow rates from LC-PAST were greater than those at LC-PINE when flows were above 1.7 mm (at 0.09% exceedence) during the pretreatment period and above 0.04 mm (at 2.4% exceedence).

Conclusions

Afforestation of grazed grasslands increases infiltration and ET. Increases in infiltration reduced total storm flow and peak flow rates, and delayed times to peak outflow. Increases in infiltration also decreased the flashiness index of the watershed. Increases in ET reduced total water yield 28% in the fourth year after planting, a year characterized by a very dry period followed by a very wet period; however, water yield reductions were not as great in the other years of the study. Water yield reductions will vary with seasons depending on weather patterns. The water yield reduction over the last three years of the study has been 15%. Continued research on this site and other paired watershed studies will more accurately quantify the hydrologic impacts of afforestation.

Acknowledgements

This work is a product of the North Carolina Agricultural Research Service, N.C. State University. Support was provided by the Instituto Nacional de Investigación Agropecuaria (INIA), Weyerhaeuser Foundation, and Weyerhaeuser Uruguay. The work is also in collaboration with the Agronomy Faculty of the Universidad de la Republica in Montevideo, Uruguay.

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