This is not a peer-reviewed article.
21st Century Watershed Technology: Improving Water Quality and Environment,
Proceedings of the 29 March - 3 April 2008 Conference,
Concepcion, Chile, Publication date 29 March 2008
ASABE Publication Number 701P0208cd.
Eds. E.W. Tollner and A. Saleh

Hydrologic Impacts of Converting Grassland to Managed Forestland in Uruguay

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Abstract. Over 500,000 hectares of grassland have been converted to managed forestland in Uruguay since 1990. This study was initiated to determine the hydrologic and water quality impacts of changing land use from grassland (pasture) to pine plantation in Uruguay. Two adjacent watersheds located on the El Cerro ranch in the Tacuarembo River basin were selected for a paired watershed study. Outflow rates and water table depths are continuously measured on each watershed. Rainfall and meteorological conditions are also measured continuously on the site. During the initial pretreatment period (July 01, 2000 through June 2003) both watersheds remained in pasture. One watershed (107 ha) was planted with loblolly pine (Pinus teada L.) in July 2003, while the other (69 ha) remained in pasture. Data collected during the past 48 month period (July 01, 2003 through June 2007) represent the first four years of the treatment period. Significant changes in water yield were not observed during the first three years of the treatment period, but water yield reductions were observed during the fourth year. Most of the reductions were observed during a wet period that occurred after a prolonged dry period. Reductions in water yield occurred during storm flow events. Changes were not observed in the base flow from the watersheds. Peak flow rates from the forested land were only 25% of those observed before planting and the times to peaks were increased by 26 minutes. Data collection will continue through the growth cycle of the trees.

Keywords. Afforestation, Forest hydrology, Water yield, Paired watersheds, Loblolly pine.

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 and physiographically by native grasslands (savannah) and topography ranging from plains to rolling hills with elevations up to 500 m. About 85% of Uruguay's land mass (176,000 km2) 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 1989, the Uruguayan government instituted financial incentives for the establishment of tree plantations in an effort to diversify the rural economy. 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 600,000 ha of grasslands were planted to trees between 1990 and 2003. 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.

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. (2006) conducted a short-term (2-yr) paired study and an analysis of a long-term streamflow record before and after afforestation. In their paired study, they observed that peak flow rates from a watershed planted with eucalyptus trees were, on average, 78% lower than peak flows from a grassland watershed. Storm flow volumes were 64% lower from the forested watershed compared to those from the grassland watershed. When comparing streamflow from a 2100 km^2 watershed before and after afforestation (25% of the watershed area), Silvera et al. (2006) observed a 49% reduction in peak flow rates due to afforestation and a 44% reduction in event flow volumes. Annual water yields were 22 to 31% lower from the watershed after afforestation.

In the fall of 1999, researchers at North Carolina State University, in cooperation with the Instituto Nacional de Investigación Agropecuaria (INIA) 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 reports the hydrology of the watersheds during the pretreatment period and for the first 4 years of the treatment period.

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 Colonvade S. A. 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, base flows and water table elevations between watersheds were determined to establish the hydrology of the two watersheds before trees were planted.

The treatment watershed (D2, 108 ha) was planted with pine seedlings in July 2003. The control watershed (D1, 69 ha) remained in pasture with livestock grazing. The same relationships have been determined for the two watersheds for the four year treatment period after planting and compared to the pre-treatment period.

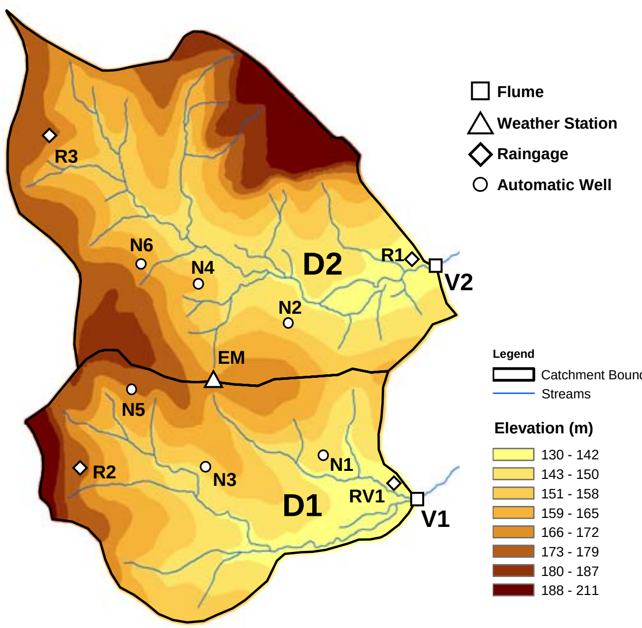

Figure 1. Location of instrumentation on watersheds: raingages, weather station, ground water wells and flumes. Topography and hydrography of watersheds are also shown.

Site Description

The topography of the watersheds is characterized by a rolling landscape with protruding rocky hillocks of basalt and sandstone. The elevation of D1 varies from 130 to 204 m, while D2 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 D2 and a similar smaller feature in the western portion of watershed D1. Land slopes mostly ranged from 2 to 15%, except in the cliff areas. The aspect of watershed D1 is primarily to the east, while watershed D2 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 0.1 to 0.35 m. Watershed D2 has a higher proportion (27%) of the shallow soils than D1 (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 Colonvade, S.A., 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 (D2) was planted with loblolly pine seedlings (*Pinus taeda L.*) in July 2003, while the control watershed (D1) remained grassland with livestock grazing. Riparian corridors, equipment access lanes, and cliff faces were not planted, resulting in 57% afforestation of watershed D2. 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 Colonvade, S.A. The area between furrows was left with grass vegetation, and the furrows were aligned perpendicular to the hillslopes. Cattle and sheep were not allowed to graze on the treatment watershed for the first four 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. The rainfall is fairly 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 December 2007.

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 D2, 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 D1.

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 USDA (1974) and Bos (1989). A Stevens Type F recorder with a float and weight system located in the stilling well on the side 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 the 1.37 m maximum height of the stainless steel HL flume, 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.

Five ground water wells were installed in the watersheds in June 2000. Wells N1 and N5 were on watershed D1 and wells N2, N4, and N6 were on watershed D2 (Figure 2). A sixth well N3 was installed on watershed D1 in September 2002. These wells were constructed of 0.1 m diameter PVC pipes buried to a depth of 1.5 to 2 meters. The water table elevations in the wells were measured using a float and weight system attached with a potentiometer linked to a data logger for recording and storing data on an hourly basis.

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 daily reference evapotranspiration or PET for a grass reference (Jensen et al., 1990).

Daily and monthly outflow volumes in millimeter equivalents for both watersheds were computed from the flow rates determined at the outlet flumes. 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:

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

where: y=monthly flow from D2 (mm), x=monthly flow from D1 (mm), m, b, and k are coefficients.

Post treatment flows on D2 were predicted with the resulting model using the measured flows from the control (D1) and differences between predicted and the observed flows were computed. Confidence intervals (95%) were calculated for individual values to test the significance of the values predicted for the treatment watershed during the treatment period. 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). The hydrograph characteristics evaluated were time to peak (TP), peak flow rate (QP), and total storm flow (TQ). TP was

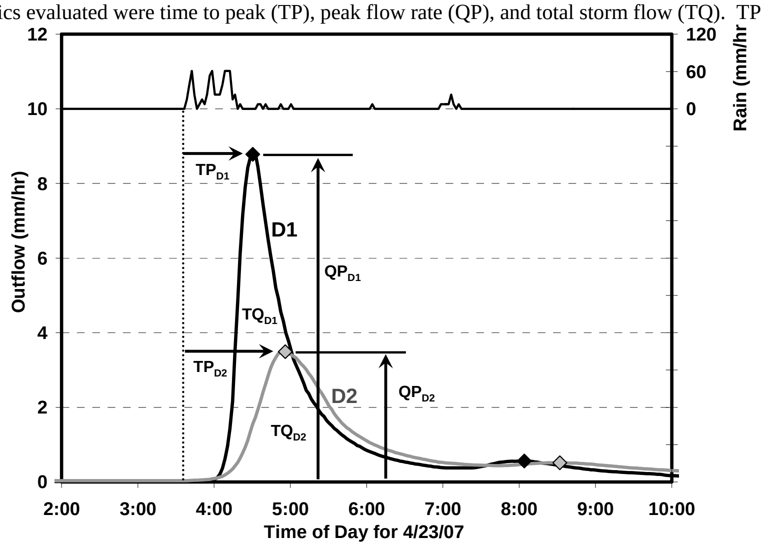

Figure 2. Outflow hydrographs observed at watersheds D1 and D2 on 4/23/07. The diagram defines the hydrograph characteristics used to compare hydrographs before and after planting of loblolly pine on watershed D2. Hydrograph characteristics shown are time to peak (TP), peak flow rate (QP), and total storm flow (TQ).

defined as the time from the beginning of rainfall to the peak flow rate of the hydrograph (Figure 2). QP was the greatest flow rate observed during the runoff event and TQ was the cumulative flow volume from the beginning of the event until the flow rate fell below 0.006 mm/hr. These characteristics were determined from flow and rain data collected every three minutes for 2001 and every two minutes for 2005 and 2007.

The differences between the times to peak at the watersheds (TP for D2 minus TP for D1) were used to compare storm hydrographs in 2001 to those in 2005 and 2007. The ratios of peak flow rates (QP for D2 divided by QP for D1) 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 D2 divided by TQ for D1) were used to compare total flow of storms in 2001 to those in 2005 and 2007.

Results

Weather and Rainfall:

Weather conditions during the pretreatment period were much wetter than during the treatment period (Figure 3). 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 amounts in these years were 22%, 40%, and 71% higher than average. Total 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 2007) was much lower than during the pretreatment period (Figure 3). Annual rainfall amounts for all four 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 amounts for the second and fourth year were near average. They were only 89 mm and 70 mm below average, respectively.

Average annual PET calculated by the Penman-Monteith method using the weather values recorded at the research site (1349 mm) was greater than the 20 year average annual corrected pan ET (1262 mm) collected from the INIA weather station in Tacuarembó. The 3 year annual average Penman-Monteith PET for the pretreatment period (1300 mm) was lower than the 4 year annual average Penman-Monteith PET for the treatment period (1389 mm).

Differences due to changes in weather between pretreatment period and the treatment period are most clearly seen by looking at the water surpluses (Rainfall minus PET) during the two periods (Figure 3). 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. For the first three years of the treatment period, water deficit conditions occurred with PET exceeding rainfall by 341 mm, 71 mm, and 436 mm, respectively. Water surplus conditions occurred in the fourth year of the treatment period with a surplus of 139 mm.

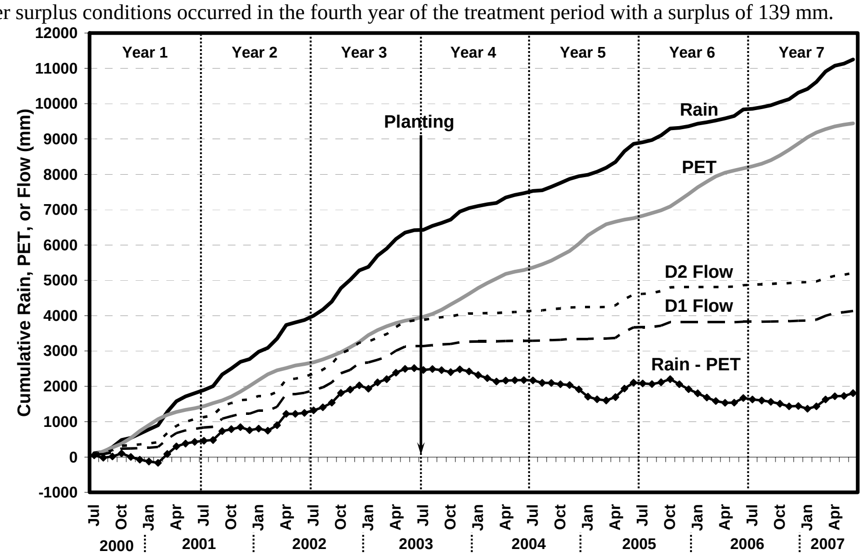

Figure 3. Cumulative monthly rainfall, PET, and outflow from watersheds D1 and D2 for the seven year study period. Cumulative excess water (Rain – PET) is also shown. This plot shows the hydrologic differences between the pretreatment (before planting) and the treatment (after planting) periods at the site.

Watershed Outflows

Outflows from both watersheds reflect the weather conditions of the study period. Average annual outflow was high (1046 mm for D1 and 1288 mm for D2) during the pretreatment period and much lower (249 mm D1 and 335 mm for D2) during the treatment period (Figure 3). 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 the impacts were expected to be small.

Outflow from the treatment watershed (D2) was consistenely greater than from the control watershed (D1) during the pretreatment period. The differences were mainly due to a higher baseflow at D2 than at D1. Possible causes for higher baseflow are lower ET from the D2 watershed or an inflow of groundwater from outside of the watershed (von Stackelberg, et al., 2007). One notable difference between the watersheds is the higher percentage of shallow soils on D2 (27%) compared to D1 (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, et al, 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 the D2 watershed from off site, but we have 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 D1 and D2, we were able to develop good relationships (Figure 4) between the watersheds for monthly flow during the pretreatment period. The relationship appeared linear when flow rates were greater 60 mm (Figure 4a); however, the relationship became nonlinear as flows decreased from 60 mm (Figure 4b). A nonlinear model was created by subtracting an exponential term from the linear model which allowed the slope of the relationship to decrease as flow increased in the low flow range. The slope of the relationship asymptotically approached the linear slope as flow increased in the high 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.

Consistent differences between the two watersheds in monthly outflow were not clearly evident in the first three years after planting (Figure 5). As in the pretreatment period, monthly flow was greater from D2 than from D1 in nearly every month. Clear evidence of changes in monthly outflow first occurred in the late summer and fall of 2007, when monthly flows from D2 were lower than from D1 for three consecutive months, February, March, and April, 2007. Monthly deviations of measured outflows from predicted outflows for D2 were below the lower 95% confidence limits for all three of these months (Figure 5). Monthly outflow from D2 exceeded monthly outflow from D1 again beginning May 2007 and remained greater than at D1 every month through December 2007. Monthly deviations of measured outflows from predicted outflows for D2 were within the 95% confidence limits after April 2007.

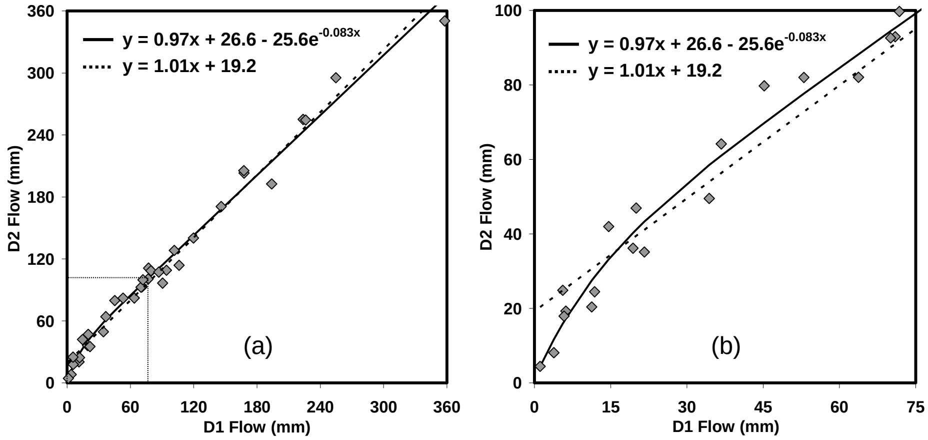

Figure 4. Plots of the relationship between watersheds D2 and D1 for monthly flow during the pretreatment period (2000-03). Linear and non-linear regression models are shown. Figure 4b. shows details of the models in the lower flow ranges

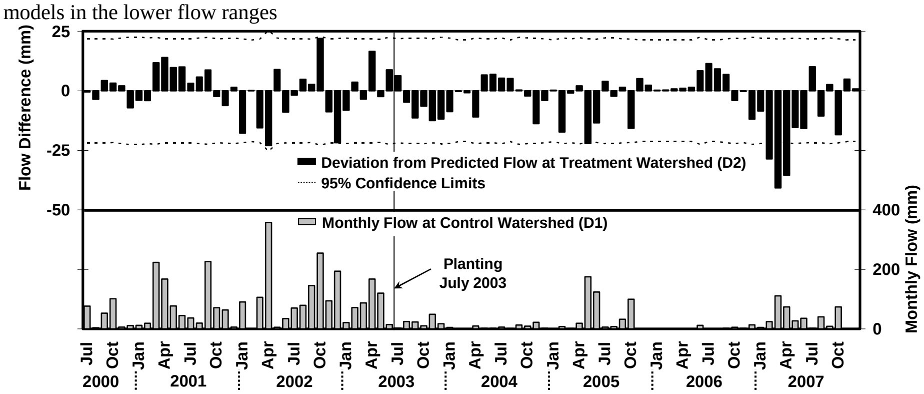

Figure 5. Monthly deviations of measured outflows from predicted outflows for the treatment watershed (D2) during the pretreatment and treatment periods. Predicted outflows and 95% confidence limits were calculated by the non-linear model. Measured monthly flow from the control watershed is also shown.

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 outflows predicted by the model from December 2006 to June 2007. This indicates that the trees transpired more water from the soil during the dry period than did the grass; therefore more of the rain water during the wet period went to replenishing the soil than to outflow. After the soil water was replenished, the monthly outflow volumes were near those predicted by the model.

Storm Hydrographs

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 (D2) were reduced and flow durations were increased during the treatment periods (Table 1). Peak flow rates from D2 were on average 1.5 times greater than those at D1 during the pretreatment period. Peak flow rates from D2 were on average only 75% of those from D1 during the wet period in 2005, and only 39% of those from D1 during the wet period in 2007. During the pretreatment period the peak flow rates from D2 occurred on average 9 minutes later than peak flow rates from D1. Peak flow rates from D2 occurred on average 20 minutes later than that from D1 during the wet period in 2005. Peak flow rates from D2 were 35 minutes later than the peak flow rates from D1 during the wet period in 2007. Total storm flow volumes from D2 were 1.6 times greater than at D1 during the pretreatment period, but where only 69% of D1 storm volumes late in the treatment period.

Discussion

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 (D2) and the grassed watershed (D1). Increases in infiltration could be caused by three factors after the trees were planted. One factor is that the grass was no longer being grazed

Table 1. 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_{D2}-TP_{D1} mm:ss	Peak Flow Rates QP_{D2}/QP_{D1}	Total Storm Flow TQ_{D2}/TQ_{D1}
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 $P<0.02$ – Student's t-Test

allowing it to grow taller and slow surface runoff from the land. Another factor is that the soil surface was no longer being trampled and compacted by livestock. The third 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.

The hydrology of the treatment watershed has changed since the trees were planted. The first changes observed were changes in the storm hydrograph characteristics on the treatment watershed only 1.5 years after planting. Increases in times to peak and decreases in peak flow rates were caused by increases in infiltration. More water was infiltrated on the treatment watershed which decreased the total storm flow and peak flow rates from the watershed and delayed the times to peak flow. The changes to the storm hydrographs on the treatment watershed were greater 3.5 years after planting. Reductions in total storm flow and peak flow rates from forested lands may reduce flooding potentials downstream.

Significant changes in the storm hydrograph characteristics were observed before significant changes in water yield were observed. Significant reductions in outflow volumes from the forested watershed were first observed during a wet period in the fourth year after planting. This period was preceded by a prolonged dry period that occurred between three and four years after planting. The observation of reduced outflow after a dry period is consistent with the theory that trees transpire more water from the soil than grass when soil conditions are dry; therefore, this flow reduction occurred due to an increase in ET from the treatment watershed. Reductions in monthly water yields will likely vary from season to season and from wet periods to dry periods. A better understanding of these patterns will lead to more effective management of water resources.

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 ET reduced total water yield in the fourth year after planting. Water yield reductions will vary with seasons depending on weather patterns. 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 Colonvade, S.A. The work is also in collaboration with the Agronomy Faculty of the Universidad de la Republica in Montevideo, Uruguay.

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