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Increased water use by ponderosa pine plantations in northwestern Patagonia, Argentina compared with native forest vegetation

Julian A. Licata^{a,*}, Javier E. Gyenge^b, Maria Elena Fernandez^b,
Tomas M. Schlichter^b, Barbara J. Bond^a

^a Department of Forest Science, Oregon State University, 321 Richardson Hall, Corvallis, OR 97331, USA

^b INTA EEA Bariloche, Grupo de Ecología Forestal, CC 277 (8400) Bariloche, Argentina

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Abstract

Ponderosa pine (*Pinus ponderosa* Doug. ex. Laws) plantations represent more than three quarters of afforestation projects in the Northwestern part of Argentinean Patagonia. Most plantations are located in the forest–steppe ecotone within the natural distribution area of cordilleran cypress (*Austrocedrus chilensis* (D. Don) Pic. Serm. et Bizzarri). The productivity of ponderosa pine plantations is much greater than that of the native cordilleran cypress forests, which would suggest a greater utilization of water resources. Our primary hypothesis was that ponderosa pine plantations have higher total annual transpiration per hectare than native cordilleran cypress stands of similar density. As secondary hypotheses we tested whether ponderosa pine stands: (1) have higher maximum transpiration rates, (2) utilize water over a longer season, (3) deplete soil water to a lower moisture content level, and (4) extract water from deeper soil layers than native cypress stands. Through continuous measurement of sap flow and of soil water content at various depths (from surface to 1.8 m), we examined the total amount of water used by four forest stands: a high density ponderosa pine timber plantation (HDPP), a low density silvopastoral ponderosa pine plantation (Silvo), a low density cordilleran cypress forest stand (LDCip) and a high density cordilleran cypress forest stand (HDCip). Measurements were carried out during 2 years that had contrasting amounts of summer precipitation. HDPP had the highest water use at the stand level, averaging 64% and 33% greater than HDCip in the wet and dry years, respectively. Higher transpiration rate but not length of the transpiration season explained the difference in total annual transpiration between species. Water depletion occurred simultaneously at all soil depths for all the plots even in the wet year. However, the HDPP plot used a greater amount of water from deeper soil layers compared to all the other plots. Our results emphasize the need for caution when planning afforestation projects at large scales, as the increase in transpiration due to conversion of native forests to high density ponderosa pine plantations could have a large impact on water resources.

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1. Introduction

The increase in global demand for paper and wood products is increasing pressure on natural forests. Afforestation with fast-growing species has been proposed as a sustainable economic alternative that would reduce the harvest of native forests (Sedjo and Botkin, 1997; Binkley, 1999; Hartley, 2002; Friedman, 2006). Worldwide, increased wood productivity is usually achieved by planting exotic species (Sedjo, 1999; Hartley, 2002; Siry et al., 2005; Fritzsche et al., 2006). However, the introduction of exotic species could lead to a

complex array of negative consequences (Le Maitre et al., 2002; Kanowski et al., 2005; Noretto et al., 2005; FAO, 2007). In semi-arid regions, for example, stands of fast-growing exotic trees may deplete already-scarce water resources. The eastern slope of the Andes in Patagonia serves as the water source for vast regions of Argentina, and large-scale afforestation efforts in this region have the potential to drastically alter regional water resource availability. There are currently ~70,000 ha of planted forests in northwestern Argentinean Patagonia, with an additional ~2,200,000 ha that could be converted to plantation forestry (Laclau and Andenmatten, 2005). Understanding the potential effects of exotic pine plantations on water resources is critical in Patagonia to prevent potential negative consequences from the expansion of planted forests.

* Corresponding author. Tel.: +1 541 737 8493; fax: +1 541 737 1393.

E-mail address: Julian.Licata@oregonstate.edu (J.A. Licata).

The Andean region of Patagonia in South America is geographically and climatically very similar to the Pacific Northwest (PNW) of North America, and most of the exotic plantations in this region utilize species from the PNW. The Andes range creates an exponential decrease in annual precipitation from west to east, which is the predominant direction of the strong winds that are typical of Patagonia (Paruelo et al., 1998). The western humid forests of the region are mostly protected in large national parks established by the Administration of National Parks of Argentina. Therefore, most of the plantations are located outside these parks in the drier forest–steppe ecotone. As a result, around 80% of the afforestation projects have used ponderosa pine, which is well adapted to dry environments like those found in the forest–steppe ecotone of Patagonia (Gallo et al., 2005).

The distribution and structure of the forest–steppe ecotone has been heavily influenced by fire disturbances (Mermoz et al., 2005). In particular, the use of fire by Native American hunters and, later, European settlers, to transform woodlands into pasture and agricultural lands has shaped the current distribution of cordilleran cypress (Veblen et al., 1999; Kitzberger and Veblen, 1999), the dominant native tree species in the area. Most ponderosa pine plantations occupy areas where cordilleran cypress forests were previously displaced by fires and sheep ranches. Natural recolonization by the cordilleran cypress is occurring in large areas of the forest–steppe ecotone, but it is uncommon in areas where high density ponderosa pine plantations have been established.

The productivity of ponderosa pine plantations is much greater than the productivity of the native vegetation they replace (Schlichter and Laclau, 1998). Wood productivity of native cordilleran cypress on intensively managed stands ranges from 4.5 to 11 m³ ha⁻¹ y⁻¹ (Loguercio et al., 1999, 2005). In contrast, annual wood productivity of ponderosa pine plantations in the same region averages 20 m³ ha⁻¹ y⁻¹ (Gallo et al., 2005), and has been reported to be as high as 40 m³ ha⁻¹ y⁻¹ (Girardin and Broquen, 1995). The higher growth rates of ponderosa pine plantations compared with native cordilleran cypress in Patagonia suggests greater water use by the pines. In forest ecosystems, water transfer from soil to the atmosphere is mainly mediated by vegetation (Unsworth et al., 2004). Therefore, an increase in transpiration due to a change in land use could lead to a decrease in available water for other uses downstream.

Higher consumption of water by tree plantations compared to natural vegetation has been reported in other parts of the world (Vertessy and Bessard, 1999; Vertessy et al., 2002; Farley et al., 2005; Noretto et al., 2005). Changes in groundwater level have also been observed following modification of forest cover (Xu et al., 2002; Pothier et al., 2003; Jackson et al., 2005; Jutras et al., 2006). Based on soil water measurements, Gyenge et al. (2002) estimated that young ponderosa pine plantations in Patagonia used about 90 mm more water through the growing season than the natural vegetation on the non-forested adjacent steppe. Physiological comparisons concerning water use among individual trees of ponderosa pine and cordilleran cypress have been done in the same study area (Gyenge et al.,

2003; Gyenge, 2005); however, no previous study has compared the consumption of water by forest stands of exotic ponderosa pine with native forests.

Although ponderosa pine plantations are mainly planted in dense stands solely for the purposes of wood production, we also evaluated a low density ponderosa pine plantation, which had been studied previously to assess the feasibility of silvopastoral systems in the region (Fernandez et al., 2002; Gyenge et al., 2002). Silvopastoral systems are not well developed in the region, but have a large potential for acceptance by landowners who traditionally work with grazing systems.

The main objective of this study was to compare the water use of a high density ponderosa pine plantation stand (HDPP) and a pine-grass silvopastoral stand (Silvo) against high and low density native cordilleran cypress forest stands (HDCip and LDCip, respectively) in Andean Patagonia through the growing season. The main hypothesis we tested was that ponderosa pine plantations have higher total annual transpiration per hectare than native cordilleran cypress stands of similar density. As secondary hypotheses, we tested potential mechanisms that would allow ponderosa pine stands to have higher transpiration. Specifically, we tested whether ponderosa pine stands: (1) have higher maximum transpiration rates, (2) utilize water over a longer season, (3) deplete soil water to a lower moisture content level, and (4) extract water from deeper soil layers than native cypress stands.

2. Methods

2.1. Study site

The study was carried out over two growing seasons (from October 2004 to April 2006) in Estancia Lemú Cuyén, Valle de Meliquina (40.29°S, 71.13°W), in Lanín National Park, Patagonia, Argentina. The precipitation regime is of Mediterranean type with approximately 80% of the annual precipitation occurring during fall and winter, mainly as rainfall.

Four plots (approximately 0.25 ha each) were installed in an alluvial plane of the Caleufu River, at an altitude of 810 m. Soils are deep with a sandy loam texture, with pebbles and small rocks (mixed with the sediments) increasing in abundance with depth. Three plots were installed the first year (2004–2005), and were comprised of a dense stand of 25-year-old ponderosa pine plantation (HDPP), a 25-year-old silvopastoral managed stand of planted ponderosa pine with grasses (Silvo), and a natural pure cordilleran cypress stand (HDCip). The second year (2005–2006), a lower density cordilleran cypress plot (LDCip) was established on a gentle slope at the base of a hill, which aimed to be more representative of the native forest stands that occupy the hillslopes of the forest–steppe ecotone of the region. In the first year, measurements started on December 1 of 2004, and ended on March 15 of 2005, while in the second year measurements were started on October 15 of 2005, and ended on April 15 of 2006. Tree densities were 1135, 2662, 350 and 668 trees per hectare for HDPP, HDCip, Silvo and LDCip, respectively. Bifurcated stems were

considered individual trees. Average dominant tree height in all the plots was approximately 15 m. The main criterion used to select the native forest plots (HDCip and LDCip) was the similarity of environmental conditions to the plots with planted pines. Thus, before deploying the measuring devices, we visually assessed the similarity of the leaf area, height, and soil type of the native forest plots to the ponderosa pine plots. Moreover, plots had to be located within a radius of 500 m from the ponderosa pine plots.

Due to the intensive measurements and the nature of the equipment required for this study (e.g. measurement systems for sap flow and soil water content requiring a central energy source and dataloggers), it was not possible to replicate the treatments. This was a case study, designed to provide detailed, stand-level measurements of water use in native and exotic pine stands at high and low densities.

2.2. Meteorological data

Meteorological data were acquired from a permanent meteorological station installed 7 km from the study plots. A portable meteorological station was located next to the permanent station to calibrate sensors and then in an open grassland near the study plots for 15 days during two different periods to check for possible discrepancies in the meteorological conditions between the two locations. The permanent station was a personalized Campbell Scientific (Logan, UT, USA) weather station with sensors for air temperature and relative humidity (Vaisala, CS500) at 1.5 m high, wind speed and direction (RM Young Wind Sentry, Model 03001-5) at 2 m, precipitation (TE525MM Tipping bucket rain gauge) at 0.4 m, solar radiation (LI200X pyranometer) at 2 m high, and soil temperature (107 L temperature probe) at 0.05 m depth. The portable station had sensors for air temperature and relative humidity (Vaisala, HMP45A) at 1.5 m high, wind speed (Met One Instruments, Grants Pass, OR, USA, model 014A-L) at 2 m high, photosynthetically active radiation (Li-190SA) at 2 m high, and precipitation (TE525MM Tipping bucket rain gauge) at 0.4 m. Sensor output was recorded every 15 s and averaged every 30 min with a Campbell CR10X datalogger. Long-term data (23 years of monthly precipitation averages) were obtained from a meteorological station (70 km south of the study site) at the Bariloche airport, managed by the Argentinean National Meteorological Service.

2.3. Leaf area index

The leaf area index (LAI) of all the plots was calculated using the total leaf biomass and the specific leaf area (SLA) of total leaf area for each of the plots. The SLA of cordilleran cypress plots was measured from 20 samples of foliage collected from full sun and shaded areas of the canopy, from 10 different trees at both cordilleran cypress plots. Leaf areas were determined using ImageJ software (Rasband, 2006) on digital images of the green foliage. SLA of ponderosa pine was obtained from Gyenge (2005), who measured that parameter in the same plots for a previous study. The mass of the dried

samples was determined using a 0.001 g precision balance. Total leaf biomass was calculated applying allometric equations described by Laclau (2003) for every tree in the plots that had DBH larger than 5 cm. Those equations were developed using trees of both species from different stands around the region, which included plots at the same location of this study.

2.4. Transpiration

We measured sap flow continuously using 20 mm constant power thermal dissipation probes (Granier, 1987). Sap flow sensors were installed in 15, 18, 18 and 24 trees, randomly selected, in the Silvo, HDPP, LDCip and HDCip plots, respectively. The sampled trees represented approximately 50% of the sapwood basal area in the plots. In eight trees of the HDCip plot that had stems of irregular circumference, multiple sensors per tree were installed to check for differences in sap flow density between the different parts of the stem rugosity (flat, convex and concave positions). There were no consistent differences in sap flow density among the flat, convex and concave positions of the stem surface. All sensors were installed in the outermost part of the xylem at 1.4 m height, on the southern side of the stems. All sensors were replaced between the two measurement years and new sensors were installed in different trees or at different positions in the same tree if no other trees were available in the plot. At least 10 cm of vertical and horizontal distance was left between old and new sensor installation placements. A ring of thermal and radiation insulation (Mexpol[®], 9 mm) was placed around the stems, covering the sensors and at least 20 cm above and below them, to avoid a thermal gradient effect on the stems. Sensor output was measured every 15 s and averaged every 30 min with a Campbell CR10X data logger and AM416 multiplexer. These data were transformed to sap flow density on a sapwood area basis following Granier (1987).

Previous studies involving several tree species found higher sap flow density in the outer part of the sapwood area than in the zone closer to the heartwood (e.g. Cermák and Nadezhdina, 1998; Jimenez et al., 2000; Irvine et al., 2002; Nadezhdina et al., 2002; Delzon et al., 2004; Ford et al., 2004). Accounting for this decline in sap flow density across the stem is particularly important for ponderosa pine because it has a large sapwood depth, usually more than five times the depth of the sap flow sensors in the trees of this study. Therefore, at the end of both seasons (beginning in January 16 in 2005, and in March 17 in 2006, for a minimum of 15 days) sap flow sensors were installed at several depths in four trees at both the HDPP and the Silvo plots. Sensors were installed in depth by drilling a 16 mm diameter hole until the desired starting depth to make the measurement. Initially, sensors were installed at increasing depth in a spiral up the stem, incrementing the depth between each sensor by 1 cm (sensors depths were: 0–2; 3–5; 6–8; 9–11; 12–15 cm). This pattern of sensor installation proved inappropriate due to heat build up during the night. Heat interference between sensors was verified by the increase in temperature during the night in unheated sensors. To remove

heat interference among sensors, only three sensors per tree were left heated. In the second year only two or three sensors were installed per tree, depending on the sapwood depth, in four other ponderosa pine trees.

Similar to other authors' findings (Ford et al., 2004; Fiora and Cescatti, 2006) the ratio between the instantaneous sap flow densities of the outmost and inner sensors was variable among hours of the day and trees. To reduce this variation, ratios between the outermost sensor and the inner sensors were calculated using the daily values from each sensor. The position of the sap flow sensor was normalized by the total sapwood depth to make comparable the ratios between sensors in trees of different sizes. Although the best fit was given by a Gaussian function, it improved the Pearson's r^2 by only 3% compared to a simple linear equation. Therefore, for simplicity a linear decrease function was used to simulate the radial variation of sap flux density across the stem (Fig. 1). Sapwood depth in the cordilleran cypress trees is much shallower than in ponderosa pine, rarely exceeding 4 cm. Consequently, the amount of error that could be produced by not accounting for the radial decline in sap flow density is much lower in cypress than pine. The same relative radial decline function was used to simulate a decrease in sap flow density in cordilleran cypress stems as in ponderosa pine stems.

Sapwood depth was measured by taking increment cores from 30 trees of each species growing adjacent to the study plots. Species-specific allometric equations derived from those measurements were used to calculate the sapwood area of trees inside the plots. Sapwood area per ground area was calculated through measurement of the diameter at breast height (DBH) of all the trees in the plots.

By integrating the sap flux density across the stem in a 1 cm increase in sapwood depth, the following function was derived to calculate a radial correction multiplier, depending solely on the stem radius.

$$\beta = \frac{\sum [(r - r_i)^2 - (r - r_{i+1})^2] (r_i - r_h) / (r_0 - r_h)}{(r^2 - r_h^2)}$$

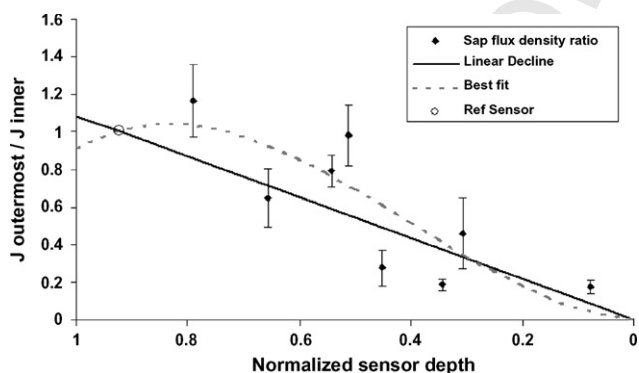


Fig. 1. Radial decline of sap flow density across the stem. X-axis represents the relative distance from the heartwood ($x = 0$) to the cambium ($x = 1$). Y-axis represents the daily sap flow density ratio of inner sensors relative to outermost sensor in the same tree. Each data point is a 15 days average. Error bars represent standard errors. Dotted line represents the best-fit function tested, and solid line represents the linear decline used in this study. Open circle represents the average position of the outermost sensors used as references.

where r is the radius of the cambium from the pith; r_h is the radius of the heartwood from the pith; r_0 is the radius of the outmost sap flow sensor; r_i is the radius from the pith of the i th iteration.

The following equation was used for scaling transpiration to the stand level:

$$E = \bar{\beta} \rho_w \bar{J} \times \text{SAI}$$

where E is transpiration at the stand level; $\bar{\beta}$ is the radial correction multiplier for the average DBH of the stand; ρ_w is the density of water; \bar{J} is the average sap flow density of the stand; SAI is the sapwood area per ground area.

The lengths of the measurement periods were different in the 2 years; the second year measurements were started a month and a half earlier than the first year and ended a month later. Therefore, in order to compare total seasonal transpiration between the 2 years, estimates of total transpiration were standardized to a 180-day period from the middle of the spring to the middle of the fall (the "transpiration season"). All the daily values throughout this period of time were added to get the total transpiration for each season. Missing daily values within the measurement period (<2% of the data) were assumed to be equal to the 30-day average around the day of the missing data; missing daily values for the beginning and the end of the first year, when there were no measurements available, were assumed to be equal to the average of the first and last 15 days of measured data from that same year, respectively. Data from the second year of measurements suggested that this was a reasonable assumption.

2.5. Soil water depletion

Multiple sensor, frequency domain capacitance probes (Sentek EnviroSMART, Sentek Pty Ltd., Adelaide, Australia) were used to continuously monitor volumetric soil water content; data were recorded every 15 s and 30-min averages were stored in a CR10X Campbell Scientific datalogger. The Sentek measurement system employs long probes, which are inserted into 5.5 cm diameter PVC casings; the casings, in turn, are installed in holes augured into the soil. Our probes were 2 m long, with six sensors per probe at 10, 20, 40, 80, 140, and 180 cm depths. In the first year, we used four probes randomly distributed in each of the three plots. In the second year, we used three probes in each of the four plots. In the LDCip plot we could not use the 180 cm sensor due to shallower soils.

Daily average soil water content was determined for each sensor, and soil water depletion was calculated as the difference between successive days. We calculated the total volumetric water content through the 2 m depth of each probe assuming a linear gradient of soil water content between sensors.

Gravimetric measurements of soil water content were carried out during the second season to perform a site-specific calibration of the Sentek EnviroSMART sensors. A total of 642 soil samples were collected with an auger at approximately 60 cm from the probes, at intervals of 20 cm up to a depth of 160 cm, every 2–3 weeks throughout the second year of

measurements. Samples were dried at 105 °C. The calibration equation used was:

$$WC_{ss} = 1.0752 \times WC_{stk} + 4.766, \quad r^2 = 0.7297, \quad P > 0.001.$$

where WC_{ss} is the percent of volumetric water content derived from soil samples; WC_{stk} is the water content reported by the Sentek sensors using the manufacturer's calibration.

2.6. Reference evapotranspiration

The FAO Penman-Monteith method was used to calculate values of "reference evapotranspiration" (ET_{ref}) following the procedure detailed in FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) for daily climatic data. ET_{ref} represents the maximum potential evapotranspiration of a hypothetical reference crop, with no water deficiency, growing under the same meteorological conditions as measured in the field site.

3. Results

Stand structure was markedly different between the high and low density plots and relatively similar between plots of similar density (Fig. 2). LAI was approximately doubled in the high density plots (9.1 and 9.0 for HDCip and HDPP, respectively) compared to the low density plots (4.6 and 3.1 for LDCip and Silvo, respectively; Fig. 2). Basal area was 97, 65.5, 50.7 and 27.5 $m^2 ha^{-1}$ for HDCip, HDPP, LDCip and Silvo, respectively, while sapwood area was 43.7, 59.7, 21.7 and 25.9 for HDCip, HDPP, LDCip and Silvo, respectively, resulting in a lower leaf area per sapwood area in ponderosa pine (0.15 and 0.12 $m^2 cm^{-2}$ for HDPP and Silvo, respectively) than in cordilleran cypress plots (0.21 $m^2 cm^{-2}$ for both HDCip and LDCip). For any particular measure of stand density, high density plots were about twice the value of the low density plot for the same species. Comparability of densities between species was based on the similarity of LAI. However, high and low density is used throughout the manuscript as a qualitative descriptor of the plots and not as a variable causal of response.

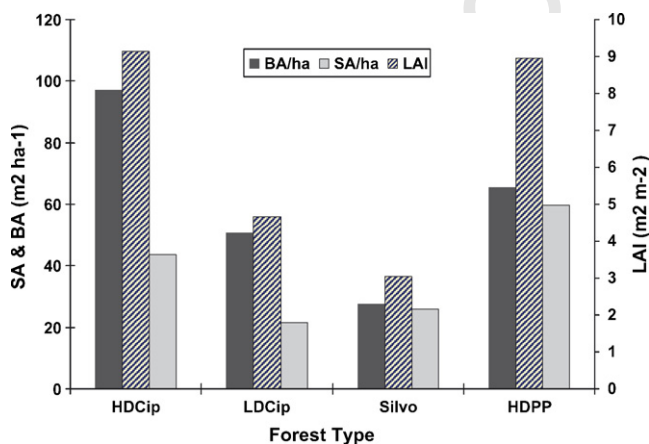


Fig. 2. Stand density. Basal area (BA, $m^2 ha^{-1}$), sapwood area (SA, $m^2 ha^{-1}$) and leaf area index (LAI, $m^2 total leaf area m^{-2} ground area$) for the measured plots.

Precipitation was different between the two growing seasons. While the total cumulative precipitation from June to July was only 101.3 mm for the 2 years of measurements, summer precipitation between November and March was 154 mm greater in the second year (2005–2006) (Fig. 3). Moreover, the first (dry) and second (wet) seasons of measurements correspond with the lower and upper limits of 1 standard deviation of the 23-year mean summer precipitation.

The HDPP plot had the highest total cumulative transpiration of all the plots in both years. Total estimated transpiration for the dry year (2004–2005) was 479.4, 361.6 and 332.9 mm for HDPP, HDCip and Silvo, respectively, compared with 901.6 mm for ET_{ref} . Total estimated transpiration for the wet year (2005–2006) was 657.8, 402.3, 394.8, 252.7 mm for HDPP, HDCip, Silvo and LDCip, respectively, compared with 851.7 mm for ET_{ref} .

As a consequence of more cloudy, rainy and cooler weather the second year, ET_{ref} decreased by 6% between the first and second year. However, all of the plots showed a notable increase in total transpiration in the second year. Total transpiration increased by 37%, 11% and 19% for the HDPP, HDCip and Silvo plots, respectively, between years one and two, thus enhancing the difference in transpiration between the HDPP and the rest of the plots.

During both years, ET_{ref} was greater than the actual transpiration rate for all the sites throughout the whole season (Fig. 4). During the dry year, the daily transpiration rate of HDPP was greater than HDCip plots for the first two thirds of the measurement period. The Silvo plot had lower daily transpiration rates than HDPP and HDCip until the middle of the summer. Over this time, transpiration rates in the HDPP and HDCip plots steadily declined, while the transpiration rates of the Silvo plot remained relatively unchanged. In early February, transpiration rates of all plots were fairly similar (Fig. 4); thereafter, the Silvo plot had higher transpiration rates than both

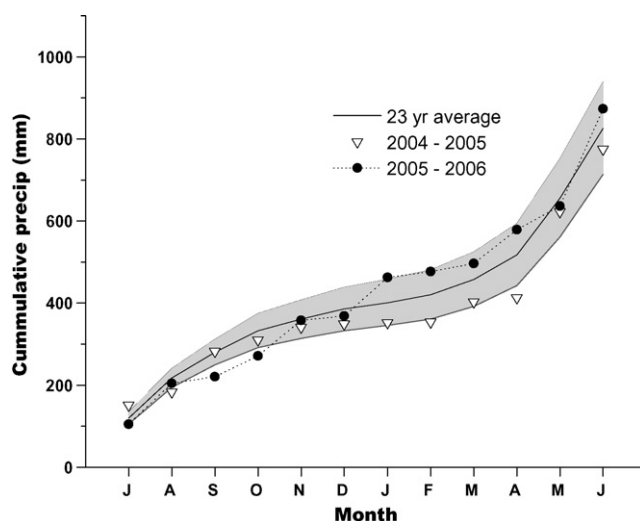


Fig. 3. Monthly cumulative precipitation of the measurement seasons compared to historic records (23 years monthly average) of precipitation data for Bariloche, Argentina (approximately 70 km south from study site). Grey area represents ± 1 standard error. Normal years show a Mediterranean regime of precipitation with a notorious summer drought (December–March).

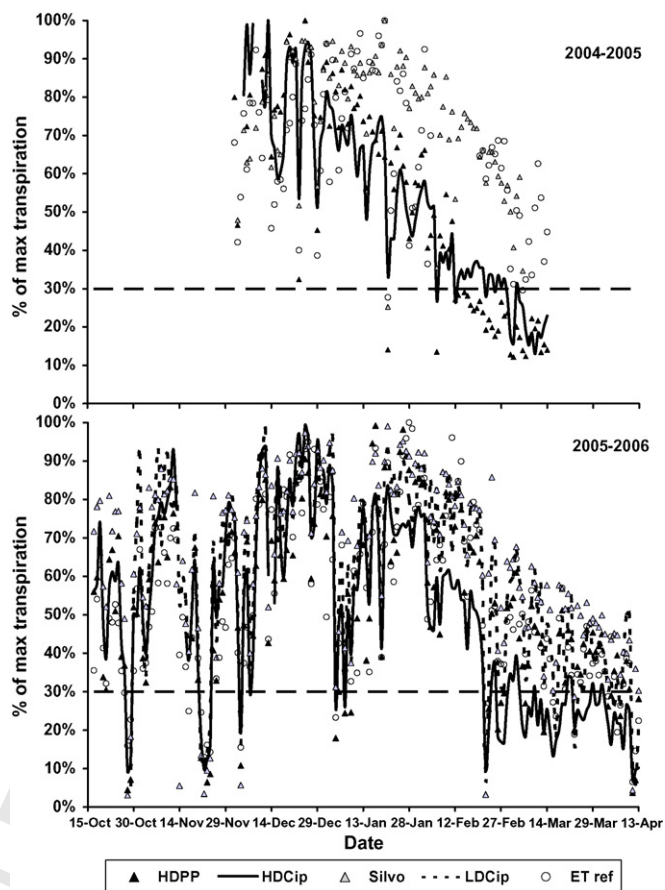
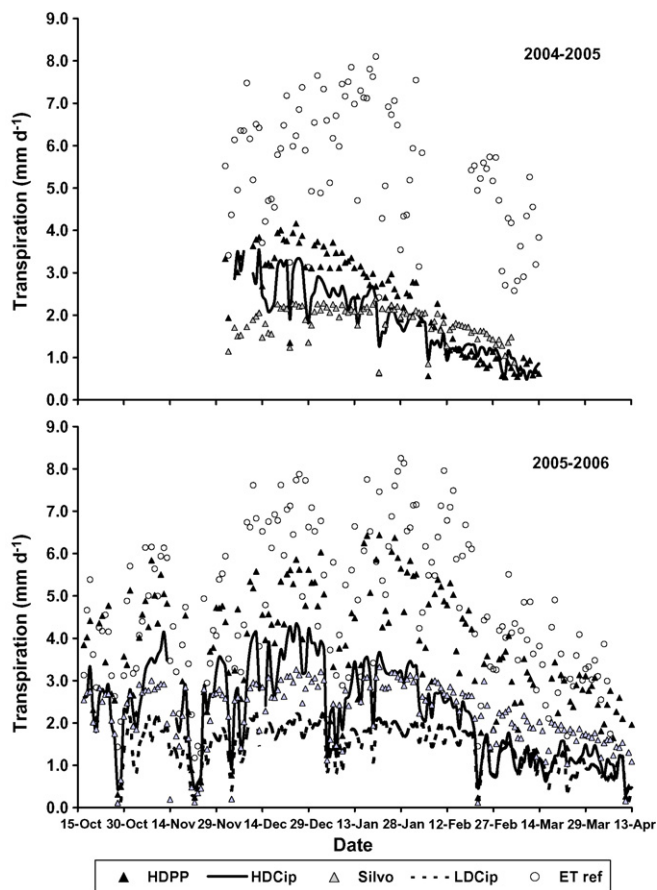


Fig. 4. Daily transpiration per plot (mm d^{-1}). Upper chart is 2004–2005 (normal dry summer season). Lower chart is 2005–2006 (wet summer season). Open circles represent the potential evapotranspiration, solid triangles HDPP, grey triangles Silvo, solid line HDCip, and dotted line LDCip. The response to greater soil water content availability in the second year was more pronounced in the ponderosa pine sites (both HDPP and Silvo). Note that in the second season measurements were started earlier in the spring.

Fig. 5. Percent transpiration relative to maximum transpiration of the season per site per day. Etr_{ref} was standardized relative to the maximum calculated ETr_{ref} rate of each season. Upper chart is season of year 2004–2005 (dry summer year). Lower chart is the 2005–2006 (wet summer year). Open circles represent the potential evapotranspiration, solid triangles HDPP, grey triangles Silvo, solid line HDCip, and dotted line LDCip.

HDPP and HDCip plots until the beginning of the fall rains in March.

In the wet year, HDPP had the highest daily transpiration rates throughout the whole growing season, and the LDCip site had the lowest. The Silvo and HDCip plots showed a pattern of seasonal transpiration similar to the previous year, but the Silvo plot transpiration started to be higher than the HDCip 10 days later than the previous year (Fig. 4).

To compare the length of the “transpiration season” among plots, we expressed transpiration rates as a percent of the daily maximum of each season for each site, and arbitrarily defined as the end of the season whenever the daily values dropped and remained below 30% of the season’s maximum. There were no consistent differences in length of the transpiration season among sites of similar densities using this criterion. While in the dry year the transpiration season was 15 days shorter at HDPP than at HDCip, in the wet year the season was 10 days longer at HDPP than at HDCip (Fig. 5). In both years the Silvo plot had a relatively high and steady rate of transpiration despite the summer drought period, while HDPP and HDCip rates were consistently decreasing. No differences were observed in the length of the season between the Silvo and the LDCip plots.

Despite the high frequency of rains in the wintertime, at the beginning of measurement periods of both years there was less total soil water to 1.8 m in HDPP than in all the other plots (Fig. 6). The lower soil water content in HDPP persisted for the whole season in both years. This could be caused by incomplete refilling of the soil during the winter of the water used by the HDPP in the previous year, by greater water use in springtime before the measurement period, or by a lower water holding capacity of the soil. The latter is less likely to have occurred given the proximity of the plots and similarity in parent material of the soils. For all plots, the amount of soil water available at the beginning of the measurements period in the first (dry) year averaged 100 mm lower than in the second (wet) year.

Water depletion was observed simultaneously at all measured depths for all sites in both years (Fig. 7); the amount of water withdrawn from deeper layers increased as the water content in upper layers decreased. However, water was depleted from deep layers of the soil even when there was water available near the surface. From the initiation of measurements until the first rain event in the dry year, more than 60% of the depleted water was supplied by the soil layers below 80 cm. In

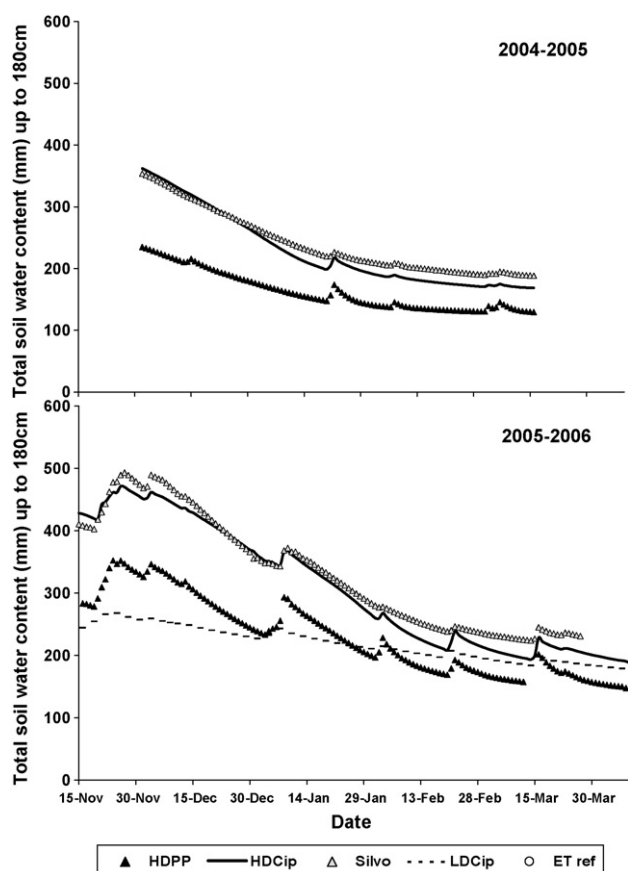


Fig. 6. Total soil water content (mm) of water stored in the soil up to 180 cm deep per site for both seasons. Calculated from daily averages of volumetric water content measurements from 3 to 4 probes per site with 6 sensors per probe at different depths (10, 20, 40, 80, 140 and 180 cm from soil surface). Solid triangles represent HDPP, grey triangles Silvo, solid line HDCip, and dotted line LDCip.

contrast, in the wet year more than 60% of the total amount of used water came from the upper 80 cm.

The soil water content measurements showed that rainfall was the only significant input of water into these systems, which allowed us to perform a mass balance analysis to compare water depletion from the soils with water use by trees, estimated from sap flow measurements. In general, the measured amount of water lost from soils to 180 cm depth exceeded the amount of water transpired by the trees (Fig. 8). This is because our measurements did not account for all of the pathways of water leaving the soil, such as deep seepage, soil evaporation or transpiration by herbaceous plants. On the other hand, in HDPP there was an apparent net negative balance between soil water depletion and transpiration in both growing seasons (Fig. 8). The unbalanced water budget in HDPP could be explained by a higher extraction of water below 1.8 m deep by deeper roots in the HDPP plot. The average daily differences between soil water depletion and sap flow were -0.98 , 0.33 and 0.16 mm d^{-1} for HDPP, HDCip and Silvo, respectively, in the first year, and -0.44 , 0.48 , 0.65 , -0.25 for HDPP, HDCip, Silvo and LDCip, respectively in the second year. In the early season of both years in Silvo, soil water depletion exceeded tree

water use (Fig. 8), most likely due to transpiration of the grasses and evaporation from the soil.

4. Discussion

In an effort to reduce the net loss of forest area, Argentina has been actively promoting forestry plantations with exotic fast growing species through subsidies and tax exemption policies (Laclau, 2003). The increase in productivity by the introduction of fast-growing species occurs at the cost of water resources in many situations (van Wilgen et al., 1996; Vertessy and Bessard, 1999; Zhou et al., 2002; Jackson et al., 2005; Nosoetto et al., 2005). This cost is particularly important for places where water is a limiting resource, such as in Mediterranean ecosystems like the forest–steppe ecotone of Argentinean Patagonia.

In Northern Argentinean Patagonia, ponderosa pine, which is native to the western states of the United States of America, is used in over three quarters of afforestation projects (Gallo et al., 2005). Ponderosa pine plantations have approximately four times the productivity of native cordilleran cypress growing in optimal conditions (Girardin and Broquen, 1995; Loguercio et al., 2005). As carbon uptake and water loss by plants occur mainly through the same pores, the stomata, we hypothesized that transpiration of ponderosa pine would be substantially greater than that of cordilleran cypress growing under similar conditions.

As expected, our measurements showed greater use of water resources throughout the year by ponderosa pine compared to the native cordilleran cypress plots growing under similar conditions and comparable levels of stand density. Differences in transpiration among stands were enhanced during the year with higher precipitation during the summer, when all the plots followed a seasonal transpiration pattern similar to a crop with no water limitations. While in the dry year HDPP had 33% greater total transpiration than the HDCip, that difference was almost doubled (64%) during the year with relatively moist summer conditions. As potential mechanisms for an increase in total annual water use, we tested the hypotheses that ponderosa pine had higher transpiration rates than cordilleran cypress, and/or that it utilizes water over a longer season. Either of these hypotheses implies that ponderosa pine is able to utilize soil water resources that are not used by native forests. Alternative possibilities are that ponderosa pine could access water from deeper soil layers, and/or that it could deplete soil water content to lower levels of soil moisture.

4.1. Transpiration rates

The greater total water use by ponderosa pine plantations compared to native cypress stands was associated with higher maximum transpiration rates throughout the transpiration seasons. Moreover, at comparable levels of stand density, transpiration rates of ponderosa pine were always higher than that of cordilleran cypress, suggesting a higher maximum stomatal conductance of ponderosa pine trees given the similar LAI for pine and cypress forests at comparable levels of stand density.

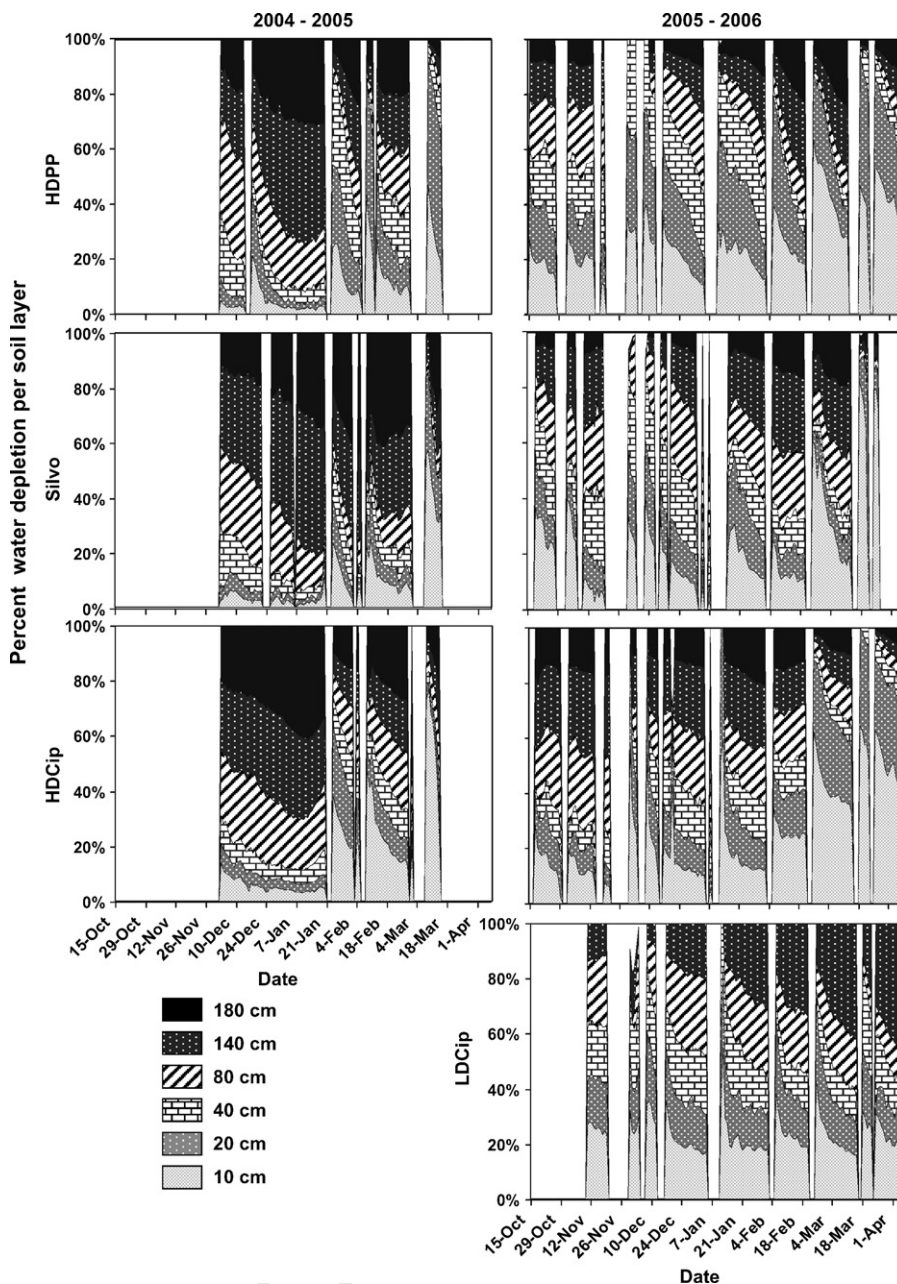


Fig. 7. Relative daily water depletion from individual layers in the upper 180 cm of the soil, calculated from daily averages of soil volumetric water content measurements. Blank areas represent periods without measurements, or rain events plus 2 days, where water depletion was not calculated.

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Stand-level maximum transpiration rates in the HDPP plot of this study were from 1.6 to five times greater than the values reported for ponderosa pine forests in North America (Anthoni et al., 1999; Ryan et al., 2000; Law et al., 2001; Irvine et al., 2002, 2004; Kurpius et al., 2003; Simonin et al., 2007).

The increase in transpiration rates between the dry and the wet year were noticeably greater in the high density pine compared to the high density cypress (37% and 11% increase, respectively), suggesting that it was capable of utilizing water resources at a faster rate when they were available, and that it was more sensitive to drought than the native forest. This could imply larger interannual fluctuations in productivity of ponderosa pine plantations compared to native cordilleran

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cypress forests. The differences in measured transpiration between the 2 years may be explained by a much larger depletion of water from the surface soil layers during the early to middle spring of the dry year (2004), even before our measurements were initiated. The lack of rainfall throughout the growing season kept the upper soil dry. This result is consistent with results reported by Warren et al. (2005), who found that the amount of water used by ponderosa pine was strongly dependent on water potential at 20 cm of soil depth, even when there was abundant water available to deeper roots. A potential explanation for this pattern is that the early depletion of soil water content during the dry year could have led to a change in soil–root resistance through the remainder of

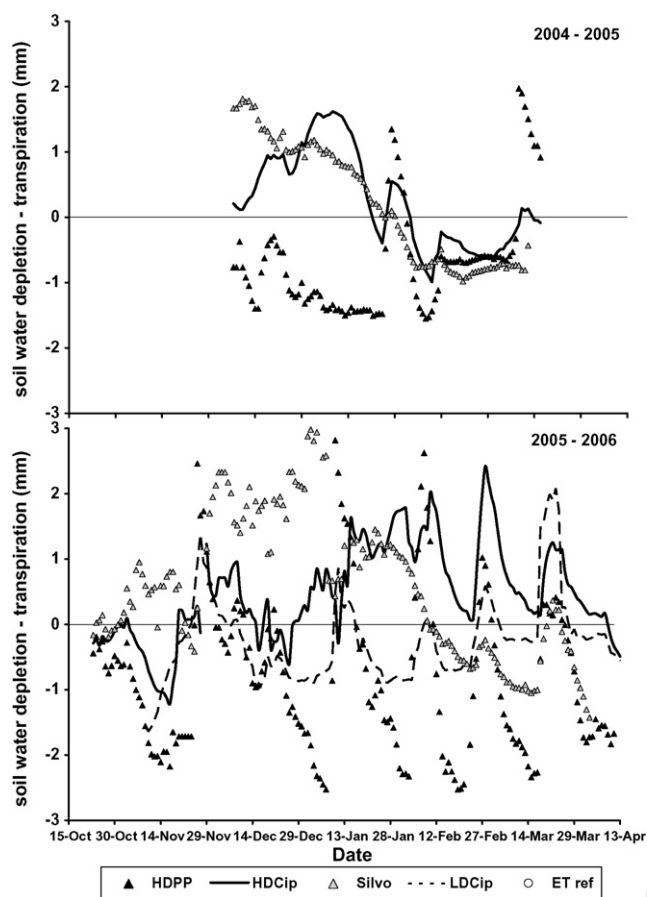


Fig. 8. Mass balance analysis. Difference between soil water depletion and sap flow estimates of water use (mm d^{-1}). Positive values represent a higher estimate of water depletion from soil measurements than transpiration estimates from sap flow measurements. Solid triangles correspond to HDPP, grey triangles to Silvo, solid line to HDCip, and dotted line to LDCip.

the season. It is well known that soil water conductivity decreases exponentially with water content depletion (Saxton et al., 1986; Brandyk et al., 1989). Furthermore, as the upper soil layers become depleted of water, the active root surface area to leaf area ratio also decreases, thus increasing the total resistance of the water pathway.

4.2. Length of the transpiration season

In a Mediterranean climate, where summer precipitation is low, the length of the transpiration season is often determined by the total amount of soil water that is available in the soil. It is possible for two species with similar rates of stand-level transpiration to have different annual water usage if one of them can sustain transpiration longer into the summer drought period. Similarly, it is possible for two species with different maximum transpiration rates to have similar annual water usage. A possible consequence of high maximum transpiration rates, such as in the dense ponderosa pine plantation of our study, might be a shortened period of active transpiration, which would ultimately result in similar total water use by the different stands, only distributed differently over time. However, for the pines to acquire more water over a similar

length of season as the native trees would require an ability to extract water either at lower tensions or from greater depths.

Our results showed that the length of the transpiration season was similar for the high density ponderosa pine and native cordilleran cypress plot. The greater transpiration by pines was not simply a result of a longer period of transpiration. Also, there was no evidence of a tradeoff between high transpiration rates and a shorter season of transpiration. The ponderosa pine trees must have been able to extract more water from the soil throughout the season.

We did find different lengths of transpiration seasons between the high density pine and the silvopastoral plots during the dry year, when the HDPP showed signs of water stress and the Silvo did not. Moreover, although the silvopastoral and high density cypress plots used approximately the same total amount of water throughout the season, the silvopastoral plot followed temporal trend similar to that of a crop with no water limitations (ET_{ref}) throughout the summer, while the high density cypress stand sharply reduced its rate of transpiration in the second half of the summer. This pattern of sustained transpiration in the silvopastoral plot throughout the drought season is consistent with a previous study, which showed that ponderosa pine trees growing in low density plantations in Patagonia are able to sustain consistently high transpiration rates from spring to autumn (Gyenge et al., 2003). During the second year of measurements when water was more plentiful, all stands followed the ET_{ref} temporal trend more closely.

4.3. Access of water from soil layers

As the input of water to these ecosystems is mainly through precipitation during the winter and fall, a higher total annual transpiration can imply greater extraction of water from soil reserves. We examined two hypotheses (not mutually exclusive) as possible strategies for ponderosa pine to withdraw more water from the soil than cordilleran cypress: deplete soil water content to lower levels of soil moisture; or extract water from deeper soil layers.

Concerning the first strategy, the soil water content data gave us contradictory results. Although the high density pine plantation ended up with a lower level of soil water content in both years than the high density cypress, the low density silvopastoral plot had a higher level of soil water content than the low density cypress at the end of the season. Our results suggest that ponderosa pine are indeed able to deplete water to a lower soil water content level than the native cordilleran cypresses, but that the available soil water was sufficient to last throughout the season for the pines in the silvopastoral system.

To investigate the second hypothesized strategy, we measured the soil water content at six depths continuously over the two growth years, to a maximum depth of 1.8 m. The relative contribution of each soil stratum to daily total water depletion did not show any conclusive pattern of differential water use by depth per species, suggesting that both species could access water up to a 1.8 m of depth.

However, a mass balance examination of the water cycle in our study plots suggests another interpretation. In the two

655 cypress plots there was a close match between estimated
656 depletion of water from the soil and total use of water by trees.
657 However, in the high density pine plot, transpiration estimated
658 from sap flow greatly exceeded the soil water content depletion
659 estimated from measurements in the 1.8 m soil profile. This
660 difference between the soil water depletion and sap flow
661 estimates suggests that approximately 33% in the dry year and
662 24% in the rainy year of the total annual water consumed by
663 trees in the high density pine plot was extracted by deep roots
664 below 1.8 m (the maximum measured in this study). In the case
665 of the silvopastoral plot, the reverse situation occurred at the
666 beginning of both seasons; soil water content depletion
667 exceeded estimated water use by trees. This is likely due to
668 evapotranspiration from soil and grass. If true, the partitioning
669 of water resources in the Silvo plot over the season would
670 amount to 84% of transpiration by trees and 16% of
671 evapotranspiration from soil and grasses. It is also possible
672 that deep drainage could have accounted for some additional
673 soil water losses in the silvopastoral plot.
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675 The mass balance approach supports the hypothesis that
676 ponderosa pine can access soil water from deeper soil layers
677 than can cordilleran cypress. Schulze et al. (1996) in a study
678 along a precipitation gradient in Patagonia also found that
679 although native woody species had deep roots, they did not find
680 use of water from deep soil depths. Despite the fact that their
681 conclusions were derived from a period of time when water was
682 available at the upper layers of the soil, it suggests the
683 possibility that native woody vegetation in Patagonia makes
684 limited use of deep soil water resources.

685 4.4. Management implications

686 Despite the limited scale and scope of this case study, our
687 results emphasize a need for caution when planning afforestation
688 projects at large scales. The management practices used in
689 the high density ponderosa pine plantation plot in our study are
690 representative of those used in ponderosa pine plantations
691 throughout Northwestern Patagonia, Argentina. If the differ-
692 ences in transpiration between treatments found in our study
693 were extrapolated across a large region, the increase in
694 evapotranspiration due to conversion of native forests to high
695 density ponderosa pine plantations could have a large impact on
696 water resources.

697 Exports of groundwater from this region are particularly
698 important for large areas of Argentina that get water from the
699 rivers originating in this mountainous area. The dominant
700 winds in this region come from the west, carrying humidity
701 from the Pacific Ocean. The rain shadow effect of the Andes
702 causes a dramatic precipitation gradient from west to east, with
703 annual precipitation of 4000 mm at some spots at the border
704 between Argentina and Chile declining to 300 mm at the extra
705 Andean mesa only 100 km away from the highest peaks.
706 Precipitation remains consistently low across the mesa to the
707 Atlantic coast, where most of the excess water from the
708 Argentinean Patagonian Andes is discharged. Along this long
709 path, water from the Andes provides critical services for the rest
710 of the country, such as hydropower, which provides approxi-

711 mately 32% of the power consumption of the country, and
712 irrigation of around 130,000 ha of agricultural land in the
713 provinces of Neuquén and Rio Negro (Fiorentino, 2005).

714 At the watershed scale, runoff water from forested areas is
715 particularly important for the traditional long-established
716 activity of sheep grazing (Paruelo et al., 2000; Nosoetto et al.,
717 2006). The most valuable and productive areas in the region for
718 grass production are wet meadows called “mallines” (Gol-
719 luscio et al., 1998; Paruelo et al., 2000) usually located in the
720 bottom of the valleys where there is an input of groundwater
721 from the uplands (Gandullo and Schmid, 2001; Nosoetto et al.,
722 2006).

723 This study highlights the potential to reduce the consump-
724 tion of water by ponderosa pine plantations through manage-
725 ment of stand density at least up to levels that native cordilleran
726 cypress may achieve in the region. Further studies are needed to
727 assess potential management practices that would lead to a
728 sustained reduction in leaf area along the rotation period.
729 Moreover, it would be critical to explore the potential change in
730 water use efficiency with stand density in order to be able to
731 optimize the land use for both wood production and water
732 conservation. Furthermore, although this study focused on
733 estimates of evapotranspiration through sap flow and soil water
734 depletion, there are other aspects of the hydrologic cycle that
735 could be different between the native cordilleran cypress forests
736 and the fast growing exotic conifers. We are conducting parallel
737 studies to elucidate possible differences in rain interception and
738 stemflow dynamics by the different types of stands, what will
739 help to close the water budget for the different systems.

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