BOSQUE 25(2): 35-41, 2004

Water use, water limitation, and water use efficiency in a *Eucalyptus* plantation

Utilización del agua, limitación hídrica y eficiencia del uso del agua
en una plantación de *Eucalyptus*

JOSE LUIZ STAPE[1], DAN BINKLEY[2], MICHAEL G. RYAN[3], ANTONIO DO NASCIMENTO GOMES[4]

[1]University of São Paulo, CNPq, Department of Forest Science, Piracicaba, SP. Brazil 13418-970,
Phone: 55-19-3436-8679, Fax: 55-19-3436-8601, E-mail: stape@esalq.usp.br
[2]Colorado State University, Department of Forest Sciences and Graduate Degree Program in Ecology
Fort Collins, Colorado. USA 80523, E-mail: dan@cnr.colostate.edu
[3]US Department of Agriculture - Forest Service, Rocky Mountain Research Station, 240 West Prospect Street,
Fort Collins, CO. USA 80526, E-mail: mgryan@fs.fed.us
[4] Copener Florestal Ltda., Alagoinhas, BA. Brazil 48090-020, E-mail: copener@copener.com.br

SUMMARY

Millions of hectares of *Eucalyptus* are intensively managed for wood production worldwide, but the ecophysiology of resource limitation on growth remains poorly quantified. We investigated the production ecology of a 3.4- to 5.4-year-old plantation of clonal *Eucalypus grandis* x *urophylla* in northeastern Brazil on a sandy Oxisol during two years (one wet, and one with normal rainfall). We measured wood production and estimated water use (transpired water) in control and irrigated treatments. Water supply limited growth; wood biomass increased from 36.6 Mg ha^{-1} for both treatments to 107.0 and 141.0 Mg ha^{-1} after 2 years for the control and irrigated plots. Across both years, irrigation increased wood productivity by 52% (42.8 Mg ha^{-1} yr^{-1} *versus* 28.1 Mg ha^{-1} yr^{-1}). Water use was similar between the control and irrigated treatments during the wet year, but irrigation increased water use by 37% in the normal rainfall year. The efficiency of water use (wood production per m^3 of transpired water) in the control treatment increased from the normal year (1.8 kg wood/m^3 of water) to the wet year (3.2 wood/m^3 of water), and irrigation increased water use efficiency by 18% in the wet year, 75% in the normal year, and 32% across both years. In combination with prior work on water use efficiency across a geographic gradient in rainfall, these irrigation results indicate that increasing water use efficiency should be expected with increasing water use by *Eucalyptus*.

Key words: forest water use, water use efficiency, irrigation, potential productivity.

RESUMEN

Millones de hectáreas de *Eucalyptus* son intensamente manejadas en el mundo entero para la producción de madera, pero la ecofisiología del efecto de la limitación de los recursos naturales en su crecimiento continuo, poco cuantificados. Fue estudiada la ecología de la producción de un plantío clonal de 3,4 años de *Eucalyptus grandis* x *urophylla* en un terreno arenoso, durante dos años (lluvioso y otro normal) en el noreste del Brasil. La producción de madera fue medida y estimado el uso del agua para el bosque (agua transpirada) en los tratamientos control y bajo riego. La disponibilidad hídrica limitó el crecimiento, y la biomasa leñosa creció de 36,6 Mg ha^{-1} para los dos tratamientos, para 107,0 y 141,0 Mg ha^{-1} después de 2 años, para los tratamientos control y bajo riego, respectivamente. El promedio de la productividad para los 2 años fue 52% superior para el tratamiento bajo riego (42,8 Mg ha^{-1} año^{-1} *versus* 28,1 Mg ha^{-1} año^{-1}). El uso del agua fue similar entre los tratamientos control y bajo riego durante el año lluvioso, pero la irrigación aumentó el uso del agua en 37% en el año con precipitación normal. La eficacia del uso del agua (producción de madera por m^3 de agua transpirada) en el tratamiento control aumentó en el año normal (1,8 kg madera/m^3 de agua), en el año húmedo (3,3 kg madera/m^3 de agua), y la irrigación aumentó la eficacia del uso del agua en 18% en el año lluvioso, 75% en el año normal, y 32% como promedio de los 2 años. En conjunto con nuestro trabajo anterior sobre la eficacia del uso del agua por un gradiente de precipitación, estos resultados indican que una eficacia superior del uso del agua se debe esperar con el aumento del uso del agua por el *Eucalyptus*.

Palabras clave: uso del agua, eficiencia del uso del agua, irrigación, productividad potencial.

INTRODUCTION

Forest plantations currently cover approximately 1% of the tropics (40-50 million hectares), supporting the increasing local and global wood demands (1, 2). *Eucalyptus* is the dominant genus of hardwood tropical plantations, but despite the vast silvicultural knowledge, we know little about the ecophysiology of stand-level water use, limitation, and wood production per unit of water used (3). For example, in an earlier paper (4) we examined the rate of water use and wood production along a rainfall gradient of 850 to 1650 mm yr^{-1} in northeastern Brazil. Wood production increased along this gradient by about 2.3 Mg ha^{-1} yr^{-1} for each 100 mm increase in precipitation, and the efficiency of water use increased by 2-fold across the gradient with increasing water use. Did this increased efficiency of water use across the gradient represent a response to increased water supply itself, or to a set of confounding site factors across the gradient? In this paper, we addressed this question by supplementing the supply of water within a single stand to determine the rate of water use, water limitation, and efficiency of water use in producing stem wood.

MATERIAL AND METHODS

The study site is located on the northeastern coast of Bahia State, Brazil, about 20 km SW of Entre-Rios (11°58'S, 38°07'W) at 250 m elevation with a mean annual temperature of 25.3 °C and an average rainfall of 1040 mm yr^{-1} (figure 1). The slopes are gentle (< 3%), with deep (> 3 m), excessively drained, acidic (pH 4.3 in 0.01 M $CaCl_2$) soil classified as sandy isohyperthermic Typic Haplustox.

The plantation was established in June 1996 with an *E. grandis* x *urophylla* clone (clone COP-0321) after controlling *Eucalyptus* sprouts (a renewal condition) and weeds with herbicide. Site preparation used a chisel-like subsoiler 0.6 m into the soil (between the prior rows). The 4 month-old cuttings were produced in a shade-house and selected for uniform size (25 to 35 cm in height) (5). A 3.0 m x 3.0 m spacing was used, and fertilizer was applied twice: at planting (14 kg N ha^{-1} as ammonium sulphate, 30 kg P ha^{-1} as superphosphate, 12 kg K ha^{-1} as KCl) along the furrows, and at 6 months-old by broadcasting 38 kg N ha^{-1}, 32 kg K ha^{-1} and 100 kg Ca ha^{-1} and 50 kg Mg ha^{-1} as lime.

The irrigation treatment began when the plantation was 3.1 years-old, and the trees were 15 m tall, with aboveground wood biomass of 36.6 Mg ha^{-1} (table 1). The experimental design used 4 blocks with each block containing a rainfed - not fertilized, a rainfed - fertilized, an irrigated - not fertilized, and an irrigated - fertilized plot (5). Fertilization had minimal effect (beyond the fertilizer added prior to the initiation of this study), and because no interaction between water and nutrient regimes was observed, all variables' means were pooled across fertilization treatments, so in this paper we focus only on the irrigation effects: control *versus* irrigated treatments. Each plot was 30 m x 30 m (approximately 100 trees), with the central 36 trees being used for measurements.

Precipitation differed substantially between the two years of this study. The first year, from October 1999 to September 2000 (3.4 to 4.3 years-old), had unusually high rainfall (1770 mm, the "wet year"), while the second year (from October 2000 to September 2001, 4.4 to 5.3 years-old) had a more-typical rainfall of 1210 mm (the "normal year") (figure 1). To reduce the potential influence of the irrigation on adjacent plots, trenches (0.25 m wide x 0.80 m deep) were maintained between plots. The micro-sprinkler irrigation system was used to guarantee a minimum input of 35 mm $week^{-1}$ based on an average potential evapotranspiration of 28 ± 2 mm $week^{-1}$.

Woody biomass was estimated based on DBH (cm) and total height (H, in meters) measurements

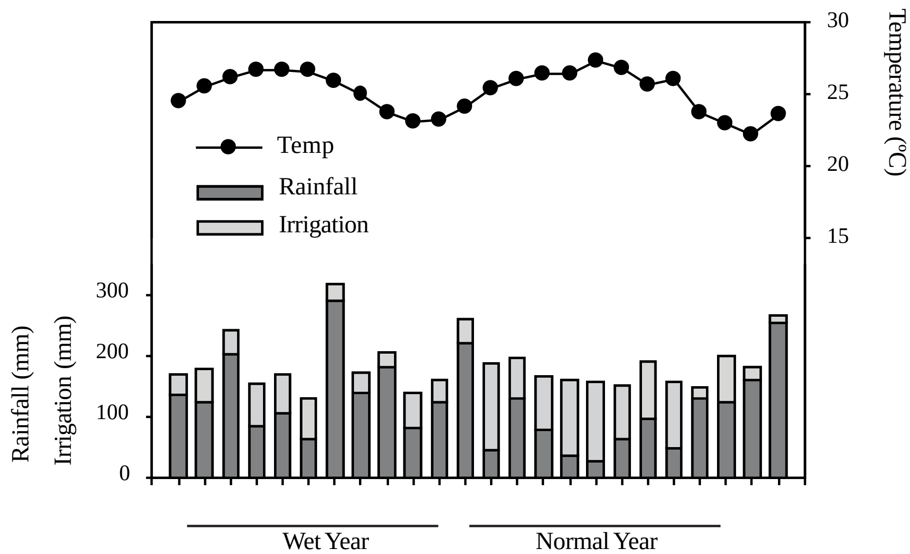

Figure 1. Monthly average temperature, rainfall and irrigation during the 24 months of the study period, characterized by a wet year (October 1999 to September 2000) and a normal year (October 2000 to May 2001).

Temperatura media mensual, lluvia e irrigación durante el período de 24 meses de estudio, caracterizado por un año húmedo (octubre 1999 a septiembre 2000) y un año normal (octubre 2000 a mayo 2001).

(done at 3.1, 4.6 and 5.4 year-old) and using a site-specific allometric equation obtained from 24 destructive sampled trees (r_ = 0.96, $P < 0.001$):

$$W = 0.0276 \times D^{2.36} \times H^{0.56} \quad [1]$$

where: W = tree wood biomass (kg)
D = diameter at breast height, DBH (cm)
H = total height (m)

Wood growth was based on the annual changes in DBH and height for each measurement tree in each plot, using equation [1].

Water use (transpiration) was determined using an algorithm based on Penman-Monteith model calibrated with data from an experimental area of *E. grandis* x *urophylla* in the region where soil moisture in 2 m profile was evaluated weekly during 1.7 years, yielding an r^2 between observed and modeled soil water content of 0.96 (5).

Analyses of variance were performed considering block, water regime as the main effects, with year as a repeated measurement factor. All analyses were performed on SAS 8.1 (SAS Institute Inc., Carry, NC, USA 2001), and Tukey's stundentized range test (HSD) was employed for multiple comparisons with a significant level of 0.05 (protecting against type I error).

RESULTS AND DISCUSSION

All biometric variables did not differ initially among plots assigned to treatments at age 3.1 (table 1); aboveground wood biomass averaged 36.6 Mg ha^{-1}. At 5.4 years, wood mass in control treatment averaged 107.0 Mg ha^{-1}, compared with 141.0 Mg ha^{-1} for irrigated plots (coefficient of variation of only 4.6%). The dominant height at 5.4 years-old increased from 24.8 m to 27.9 m (table 1).

Water supply limited growth of the trees in the control treatment to 86% of the growth achieved with irrigation during the wet year (figure 2), even though total water use through the year did not differ between treatments (1261 mm yr^{-1} of transpiration, figure 2). Water limitation on growth was more pronounced in the year with normal precipitation, when the control trees reached only 42% of the growth in the irrigated treatment (figure 2). In the normal precipitation year, the control treatment transpired 894 mm yr^{-1}, compared with 1225 mm yr^{-1} with irrigation (figure 2).

TABLE 1

Diameter at breast height (DBH), height, dominant height, basal area, stocking, volume and aboveground wood biomass for water regimes at 3.1, when irrigation started, and at 5.4 years-old. Wood productions for the first (wet, October 1999 to September 2000) and second (normal, October 2000 to September 2001) study-years are showed.

Diámetro altura pecho (DAP), altura, altura dominante, área basal, existencia, volumen y biomasa para régimen de agua 3,1 y 5,4. Producción de madera para primer estudio (húmedo, octubre 1999 a septiembre 2000) y segundo estudio (normal, octubre 2000 a septiembre 2001).

Variable	Rainfed	Irrigated	Relative gain from irrigation
3.1 years-old			
DBH (cm)	10.5	10.6	–
Height (m)	14.8	15.1	–
Dominant Height (m)	15.4	15.8	–
Basal Area (m^3 ha^{-1})	9.3	9.6	–
Stocking (trees ha^{-1})	1072	1083.0	–
Volume (m^3 ha^{-1})	65.0	69.0	–
Wood Biomass (Mg ha^{-1})	35.7	37.5	–
5.4 years-old			
DBH (cm)	15.1	16.4	9%
Height (m)	23.7	26.2	11%
Dominant Height (m)	24.8	27.9	13%
Basal Area (m^3 ha^{-1})	19.2	23.2	21%
Stocking (trees ha^{-1})	1057.0	1079.0	–
Volume (m^3 ha^{-1})	203.5	266.5	31%
Wood Biomass (Mg ha^{-1})	107.0	141.0	32%
2 years study-period			
Wet Year			
Wood Production (Mg ha^{-1} yr^{-1})	40.2	47.2	18%
Normal Year			
Wood Production (Mg ha^{-1} yr^{-1})	16.0	38.4	140%

Values are means (n = 8), and values within gain showed differ at $P = 0.05$.

Irrigation increased wood growth in part by increasing water use, but the largest contribution of irrigation was in improving the efficiency of water use. Water use differed by 37% in the normal precipitation year, but wood production differed by more than 2-fold (figure 2), demonstrating the irrigation's main effect was on water use efficiency rather than on water use per se (figure 3). The efficiency of water use (kg wood produced per m^3 of water transpired) ranged from a low of 1.8 kg wood/m^3 of water transpired in the control site during the normal precipitation year, to 3.8 kg wood/m^3 of water transpired in the irrigated plot in the wet year (figure 3).

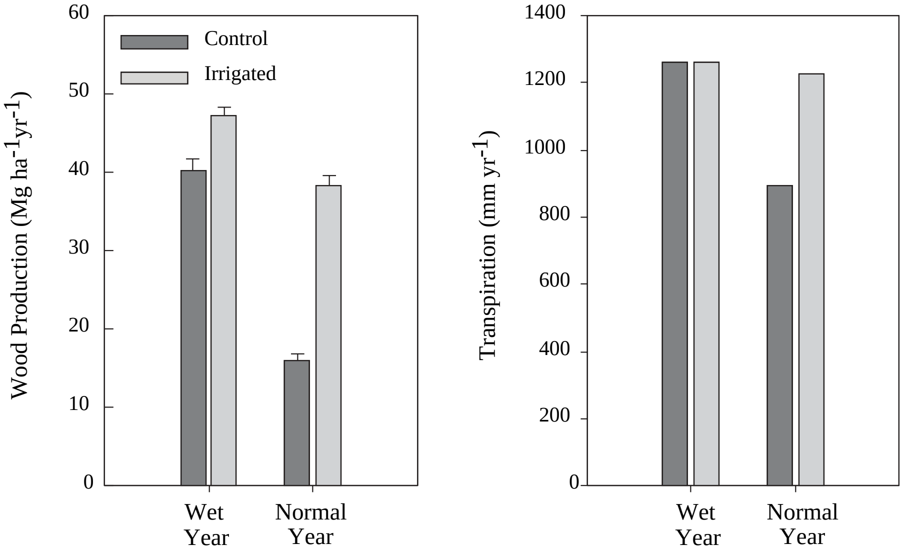

Figure 2. Wood production increased significantly with irrigation (52% across both years), especially in the normal-rainfall year (140%) (left). Water use was not altered by irrigation during the wet year, but increased 37% in the normal year (right). Error bars are standard errors of the means (n = 8).

Aumento significativo de la producción de madera con la irrigación (52% ambos años), especialmente en el año normal-lluvioso (140%) (izquierda). El uso del agua no fue alterado por la irrigación durante el año húmedo, pero aumentó un 37% en el año normal (derecha). Barras de error corresponden a error estándar de medias (n=8)

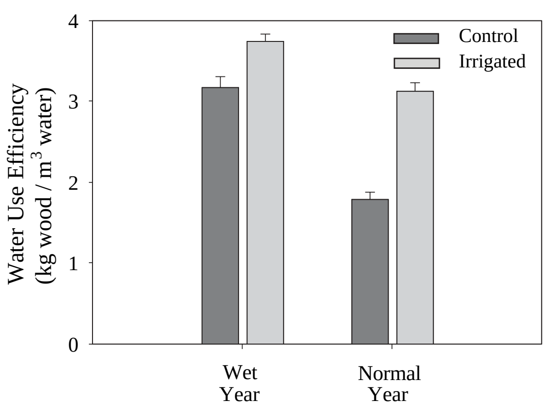

Figure 3. The efficiency of wood production per unit of water transpired was high in the wet year, and higher for the irrigated plot than for the control plot by 18% and 75%, respectively for the wet and normal years. Error bars are standard errors of the means (n = 8).

La eficiencia de producción de madera por unidad de agua transpirada fue alta para el año húmedo, y mayor para la irrigada respecto al control de 18% y 75% respectivamente para año húmedo y año normal. Barras de error corresponden al error estándar de medias (n=8).

The efficiency of water use can also be calculated as the marginal gain in wood production in the irrigated treatment as a function of the marginal increase in water use. During the normal precipitation year, the irrigated treatment used 331 mm more water for transpiration to yield an extra 22.4 Mg ha^{-1} of wood growth, giving a marginal water use efficiency for irrigation of 6.7 kg wood/m^3 of water transpired.

The efficiency of water use reported in the geographic gradient study in Brazil (4) ranged from 0.8 to 3.5 kg wood/m^3 water transpired, spanning the values observed within our stand across years. The increase in efficiency with increasing rainfall across the geographic gradient mirrored the effect of adding water within our individual site, suggesting that the improved efficiency of water use may be a general feature of increasing water use.

Other irrigation and fertilization trials with *Eucalyptus* (6-11) also reported increased wood growth associated with greater water supply. The wood increment of this clonal *E. grandis* x *urophylla* in the wet year (92 m^3 ha^{-1} yr^{-1}, figure 4) is among the highest values ever reported for forests, highlighting both the importance of water supply and the potential use of irrigation as a management option (7, 8, 12).

We suggest that more effort should be allocated to experimentation on the upper limits on forest growth (potential productivity). Even where massive investments in operational fertilization and irrigation may not be feasible, research on potential productivity can still provide important insights on the factors constraining current production.

The amount of water used by *Eucalyptus* plantations is a relevant ecological question worldwide. Nevertheless, the water use efficiency of these forests is also important, once the final wood production is dependent on both terms (4, 12). So, environmental concerns about the amount of water consumed by a forest may be interpreted differently if higher rates of water use are associated with higher efficiency of water use, as suggested on the gradient study in Brazil (4) and now corroborated on this study.

CONCLUSIONS

Average across 2 years, our irrigated experiment on a 3.4-year-old *E. grandis* x *urophylla* clonal plantation showed that wood production increased 52% by the effect of irrigation (from 28.1 to 42.8 Mg ha^{-1} yr^{-1}), while water use increase was just 15%, pointing to a 32% higher water use efficiency on the irrigated plots (3.44 kg wood/m^3 of water *versus* 2.60 kg wood/m^3 of water).

ACKNOWLEDGEMENTS

This research was supported by the National Science Council of Brazil (CNPq – 201144/97), the University of São Paulo, the McIntire-Stennis appropriations to Colorado State University, and the USDA Forest Service Rocky Mountain Station. We thank Jose Augusto Ribeiro, Jacyr Mesquita Alves and the people of Copener Florestal Ltda for all the fieldwork they contributed. This

Figure 4. Clonal *Eucalyptus grandis* x *urophylla* control plot (left, 107 Mg ha^{-1}) and irrigated plot (right, 141 Mg ha^{-1}) at 5.4 years-old, after 2 years of irrigation. The average productivity of the control treatment (8 replicates) during the 2 years-study was 28.1 Mg ha^{-1} yr^{-1}, while the irrigated ones averaged 42.8 Mg ha^{-1} yr^{-1}. Across both years, the average 52% relative gain from irrigation on wood production was obtained with just 15% increase in water use, due to a 32% higher water use efficiency of *Eucalyptus* on the irrigated plots.

Control de clones *Eucalyptus grandis* x *urophylla* (izquierda, 107 Mg ha^{-1}) e irrigada (derecha, 141 Mg ha^{-1}) a 5,4 años, después de dos años de irrigación.

project is also part of the Brazil Eucalyptus Potential Productivity Project (BEPP), which studies the ecophysiological factors that control *Eucalyptus* gross–, net– and wood primary productions.

REFERENCES

(1) FAO. *State of the world's forests*. Rome, Food and agriculture organization of the united nations. 1999. 146 p.
(2) FOX, T. R. Sustainable productivity in intensively managed forest plantations. *Forest Ecology and Management*, 2000, vol. 138, p. 187-202.
(3) BEADLE, C. L., C. R. TURNBULL. Comparative growth rates of eucalyptus in native forest and in plantation monoculture. In CALDER, I.R., R.L.HALL, P.G. ADLARD. *Growth and water use of forest plantations*. Chichester, John Wiley, 1992, p. 318-331.
(4) STAPE, J.L., D. BINKLEY, M.G. RYAN. *Eucalyptus* production and the supply, use and the efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *Forest Ecology and Management*, 2004, vol. 193, p. 17-31.
(5) STAPE, J. L. Production ecology of clonal Eucalyptus plantations in northeastern Brazil. Ph.D. Thesis. Colorado State University, Fort Collins, 2002, 225 p.
(6) PEREIRA, J. S., S. PALLARDY. Water stress limitations to tree productivity. In: J. S. PEREIRA, J. J. LANDSBERG. *Biomass production by fast-growing trees*. Dordrecht, Kluwer Academic Publisher, 1989, p. 37-56.
(7) OLBRICH, B. W., P. J. DYE, S. I. CHRISTIE, A. G. POULTER. The water use characteristics of four *Eucalyptus* clones in the Mkuzi irrigation trail. CSIR WNNR Division of Forest Science and Technology, 1992, p. 1-40.
(8) HUNTER, I. Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulensis, Eucalyptus grandis* and *Dalbergia sissoo*) as affected by irrigation and fertiliser, at 3 years of age, in southern India. *Forest Ecology and Management*, 2001, vol. 144, p. 189-199.
(9) STEWART, H. T. L., P. HOPMANS, D. W. FLINN. Nutrient accumulation in trees and soil following irrigation with municipal effluent in Australia. *Environmental Pollution*, 1990, vol. 63, p. 155-177.
(10) MYERS, B. J., S. THEIVEYANATHAN, N. D. O'BRIEN, W. J. BOND. Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree Physiology*, 1996, vol. 16, p. 211-219.
(11) HONEYSETT, J. L., D. A. WHITE, D. WORLEDGE, and C. L. BEADLE. Growth and water use of *Eucalyptus globulus* and *E. nitens* in irrigated and rainfed plantations. *Australian Forestry*, 1996, vol. 59, p. 64-73.
(12) BINKLEY, D., J.L. STAPE, M. RYAN. Thinking about resource use efficiency in forests. *Forest Ecology and Management*, 2004, vol. 193, p. 5-16.

Recibido: 03.10.03
Aceptado: 26.07.04