Water-use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements

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Abstract

South Africa has limited indigenous timber-producing forests. Recognition early in the 20th century that demand for timber had exceeded the supply available from indigenous forests forced South Africa to accelerate the expansion of its own exotic plantation forest industry. This then resulted in concerns about impacts on water resources, and led to regulation of the industry. Numerous local and international studies have subsequently proven that exotic forest plantations do consume more water than the grasslands or scrublands they typically replace, and hence reduce water yield (streamflow) from afforested catchments. Conversely, there is a widespread perception that indigenous tree species, in contrast to exotic plantation species, are water-wise and deserve to be planted more widely to expand forestry while still conserving our scarce water resources. However, data on the water-use of indigenous trees and forests is scarce and indirect. Research was undertaken to gain a broader perspective of the water-use efficiency (WUE) of a selection of indigenous tree species yielding potentially useful wood. Hourly sap flow rates (water use) over a 12-month period were recorded in a selection of indigenous tree species. Stem and branch dimensions were recorded at fixed positions at the start and end of the monitoring period, to permit whole-tree volume growth increments to be recorded. Rates of growth and water-use were used to calculate WUE and were compared to data for exotic plantation species. WUE in the indigenous species studied was comparatively low, however overall water-use was also low, making them an attractive option in water-constrained catchments.

Keywords: *Heat pulse velocity, heat ratio method, transpiration, forestry, tree growth.*

INTRODUCTION

Exotic plantation forestry is a profitable land use in many of the high-rainfall regions of South Africa, but is restricted in certain areas because of the high water-use of commercial plantations and their detrimental impact on catchment water yields. There is widespread, although un-substantiated, belief that indigenous trees may use less water than exotic trees, and would consequently have less impact on catchment water yields. Although there is much evidence to suggest that indigenous trees generally grow far slower than commercial forestry species, which are selected and bred for fast above-ground growth, very little research has been done on the corresponding water-use of indigenous species. This study was a component of a larger research project on the water use and biomass production of South African indigenous tree species (Dye *et al.*, in press). It examined the rates of growth and water-use of various indigenous species, compared to those of exotic plantation species. Results were used to calculate the relative

Water-use Efficiency (WUE), defined as utilisable wood produced per unit of water transpired, of the various species. These were compared against data for exotic plantation species measured in previous studies (Olbrich et al., 1996; Dye *et al*., 2001). Research questions posed by the study included:

- What is the variation in water-use and WUE amongst indigenous tree species?
- How does water-use and WUE of indigenous species compare to exotic plantation species?

Indigenous forests in South Africa, although limited in extent, provide multiple goods and services (natural capital, bio-diversity, building and craft materials, traditional medicines, fruits etc.). Evidence of low and efficient water-use would promote their potential as an attractive alternative forestry solution, particularly in catchments that are water-stressed. The overall efficiency of water-use for biomass production, and the net benefit of the water-used are important criteria that need to be understood to permit the evaluation of different land use scenarios.

MATERIALS AND METHODS

Site and Species Selection

Sites were selected that occurred across a broad rainfall gradient from wet to dry and included examples of both early and late successional phases of forest development. At these sites species were selected that: produce potentially valuable timber; represented both fast and slow-growing species; included evergreen and deciduous species; were relatively young; possessed well-formed canopies; and were well exposed to sunlight, being un-shaded by neighbouring trees. Conditions were sought that would mimic, as far as possible, the early phase of rapid growth under exotic plantation conditions before competition sets in, mean annual increments (MAI) peak and growth rates begin to slow. Three monitoring sites, henceforth referred to as Winterskloof, Karkloof and Weenen, were selected within the KwaZulu-Natal province, in the summer-rainfall region of eastern South Africa. Measurements were conducted for a minimum of 12 months (14 Feb 2007 to 13 Feb 2008) to incorporate seasonal variation.

The Winterskloof site (29º 35.0’ S; 30º 17.926’ E”, alt. 1 051 m.a.m.s.l) was in an area experiencing frequent summer mists, with a Mean Annual Precipitation (MAP) of 1 207 mm. Measurements were on an indigenous *Trema orientalis* (Pigeonwood) tree.

The Karkloof site (29° 18.230’ S; 30° 13.699’ E, alt. 1 253 m.a.m.s.l) is classified as southern mistbelt forest (Mucina and Rutherford, 2006). The MAP for this site is 1 273 mm (Lynch and Schulze, 2006). Measurements at this site were conducted on three indigenous trees, namely *Celtis africana* (White Stinkwood), *Podocarpus falcatus* (Outeniqua Yellowwood) and *Ptaeroxylon obliquum* (Sneezewood).

The study sites at Weenen consisted of a valley site (28° 50.842’ S; 30° 01.549’ E, alt. 1 010 m.a.m.s.l) and a higher-altitude plateau site (28° 52.613’ S; 30° 01.857’ E, alt. 1241 m.a.m.s.l). The MAP for this area is 730 mm (Lynch and Schulze, 2006). The valley site consisted of a steep, warm, north-facing slope, where measurements were conducted on an indigenous *Olea europaea* subsp. *africana* (Wild Olive) tree. The higher-altitude site at Weenen was situated on the edge of a plateau, characterized by open grassland savannah and occasional *Acacia sieberiana* trees. Sap flow measurements at this site were conducted on an indigenous *Berchemia zeyheri* (Red Ivory) tree. Table 1 provides details about the sample trees from the respective sites.

Sap Flow Measurements

The heat ratio method (HRM) of the heat pulse velocity (HPV) technique (Burgess et al., 2001) was selected for sap flow measurements because of its ability to accurately measure low rates of sap flow, expected to be the case in indigenous tree species. Sap flow monitoring systems were installed in the trees at each site, using thermocouple pairs and heater probes inserted to four different depths within the sapwood to determine radial variations in sap flow. To account for radial growth in stems the probes were completely removed and repositioned to their correct depths at the start of the growing season (October), and then rechecked periodically during the course of the monitoring period. CR10X data loggers connected to AM16/32 multiplexers (Campbell Scientific, Logan, UT) were programmed to initiate the heat pulses and record hourly data from the respective thermocouple pairs. Cellular phone modems connected to the loggers allowed remote downloading of data as well as uploading of programmes to the logger.

Heat pulse velocities derived using the HRM were corrected for sapwood wounding caused by the drilling procedure, using wound correction coefficients described by Swanson and Whitfield (1981). The corrected heat pulse velocities were then converted to sap flux densities according to the method described by Marshall (1958). Finally, the sap flux densities were converted to whole-tree total sap flow by calculating the sum of the products of sap flux density and cross-sectional area for individual tree stem annuli (determined by below-bark individual probe insertion depths and sapwood depth). Hourly sap flow values were recorded from all the trees. Periods of missing data were patched and the complete record was aggregated into daily, monthly and annual totals. Simultaneous measurements of certain meteorological variables (rainfall, solar radiation, air temperature and relative humidity) and soil water content in the top 10 cm of the soil profile, took place hourly at all sites for the corresponding period.

Stem and Branch Growth Measurements

Stem and branch biomass measurements were conducted on all the sample trees in conjunction with sap flow measurements. Initial biomass surveys were carried out shortly after the individual trees had been instrumented with the HPV systems, and the final surveys were performed one year thereafter. Stem circumferences at increasing heights up the tree, as well as branch lengths and circumferences (at their base) were measured. These measurements were converted to volumes by assuming that the stem consisted of a series of truncated cones with a complete cone at the top, while the branches consisted of individual elongated cones. The volumes of individual cones V (m^3) were calculated using:

$$V = (\pi r^2 h) / 3. \qquad (1)$$

where r is radius of the base of the cone (m), and h is height of the cone (m). The volumes of the truncated cones were calculated using:

$$V = (\pi h\, (r_1^2 + r_1\, r_2 + r_2^2)) / 3 \qquad (2)$$

where r_1 is radius of the base of the truncated cone (m), r_2 is radius of the top of the truncated cone (m), and h is height of the truncated cone (m).

The individual stem section volumes and branch volumes were totalled for each tree. This allowed for the calculation of stem, branch and total above-ground volume growth increase in the year. In conjunction with the sap flow (water-use) results this allowed the calculation of WUE (m^3 wood produced per m^3 water transpired) in terms of stem volume and stem plus branch volume increments**.** Volume increments were converted to mass according to the mean wood densities of individual species (Table 1).

RESULTS AND DISCUSSION

Weather Data

In general, the weather conditions at the three sites exhibited the seasonal patterns typical of the respective areas (Table 2). However, total rainfall for the calendar year over which sap flow and biomass increment totals were recorded was significantly above the long-term mean at Winterskloof (1 652mm), slightly below the mean at Karkloof (1 165mm) and significantly below the mean at Weenen (607mm). The implications of this on the results are uncertain. It is possible that a year of above-average rainfall would result in above-average water-use and growth (similarly with a below-average year), rendering the overall effect on WUE insignificant unless certain thresholds in water-use or growth were reached. Longer-term WUE studies would be required to verify this.

Sap Flow

Sap flow (water-use) volumes for most of the species peaked during the warm wet summer months, and declined in the cool, dry winter months (Fig. 1). This is intuitive considering seasonal fluctuations in available moisture and energy. This trend was more marked in the fully-deciduous species (*C. africana* and *B. zeyheri*). The highest monthly sap flow volumes were recorded during summer in these species, dropping to zero during the leafless winter months. The onset of sap flow in the *B. zeyheri* was later than for the *C. africana* due to the drier conditions at the Weenen site. Interestingly, although *C. africana* is a deciduous species, it had the highest 1-year sap flow total of all the sample trees. The *P. falcatus* and *P. obliquum* trees, on the other hand, showed far more conservative and consistent sap flow volumes throughout the year. *T. orientalis* is a semi-deciduous species and did not drop its leaves during the winter season, presumably due to sufficient available moisture and / or the relatively mild winter temperatures experienced at the Winterskloof site. Sap flow in this species continued throughout the winter, as was the case with the remaining evergreen species (*P. falcatus*, *P. obliquum* and *O. europaea* subsp. *africana*). Sap flow volumes in the evergreen species at the Karloof site were consistently higher during the winter months than those recorded in the evergreen *O. europaea* subsp. *africana* at Weenen, reflecting the extremely dry winter conditions at the latter site. There was a slightly lagged sap flow response (July) in the *O. europaea* subsp. *africana*, due to an unseasonal rainfall event of 28 mm in June at the Weenen site.

Growth Increments and Water-Use Efficiency

WUE results (t stem wood or stem plus branch wood per t of water transpired) for selected South African indigenous tree species (Table 3) reveal *C. africana* and *B. zeyheri* to be the two most water-use efficient species studied. A comparison of these data against those for exotic plantation species (Fig. 2) shows that the indigenous species studied were generally less efficient than exotics. However, considering that the indigenous trees sampled had not undergone genetic breeding for fast growth rates and were unmanaged in terms of typical silvicultural practices employed in commercial plantations (e.g. pruning and thinning), the results indicate useful efficiencies amongst some of the indigenous species (specifically *C. africana*, *B. zeyheri* and *P. obliquum*). For a given stem mass increment, cumulative sap flow in all the indigenous species was relatively high compared to the commercial species (Fig. 3). However, the indigenous tree annual cumulative sap flows were all less than 8.5 t $tree^{-1}$ yr^{-1}, whereas sap flows in the more productive exotic plantation trees exceeded 20 t $tree^{-1}$ yr^{-1}. Considering that some of the indigenous species were sampled under ideal growing conditions the data suggest that there may be a threshold to water-use that is substantially lower than that for exotic plantation species. Assuming that these water-use efficiencies would be retained in plantations of indigenous species, their overall water-use would remain substantially below that of productive exotic plantations, leading to a lower streamflow reduction potential. Although only exploratory at this stage, additional WUE studies on a greater variety of indigenous tree species growing under diverse conditions would be beneficial in their evaluation as alternative forestry systems, particularly in water-constrained catchments.

Acknowledgements

The research reported on here formed part of a project solicited and initiated by the Water Research Commission of South Africa (WRC), and was co-funded by the Working for Water Programme of the South African Dept. of Water Affairs and Forestry. Their support is gratefully acknowledged. Ezemvelo KZN Wildlife is thanked for allowing the monitoring of trees in their reserves. Technical advice and assistance in the field by CSIR colleagues Mr. Alistair Clulow and Mr. Lelethu Sinuka is much appreciated.

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Tables

TABLE 1. Sample tree details.

Tree Species	Site	Tree Height (m)	Breast height Stem circ. (cm)	Crown circ. (m)	Max (summer) Leaf Area (m^2)	Specific Leaf Area ($m^2\ kg^{-1}$)	Wood Density ($g\ cm^{-3}$)
Trema orientalis	W'kloof	5.65	34.4	17.28	22.26	10.25	0.422
Celtis africana	Karkloof	6.45	52.8	14.0	27.7	11.5	0.605
Podocarpus falcatus	Karkloof	6.10	60.2	10.0	35.88	5.14	0.468
Ptaeroxylon obliquum	Karkloof	5.16	37.8	8.5	18.89	8.58	0.716
Olea europaea subsp. *africana*	Weenen	5.00	40.5	12.0	14.9	5.07	0.916
Berchemia zeyheri	Weenen	5.43	62.8	19.8	36.44	15.46	0.807

TABLE 2. Monthly values of meteorological variables recorded at each site.

	Wintersskloof Site				Karkloof Site				Weenen Site			
Month	Total monthly rainfall (mm)	Mean daily max temp. (°C)	Mean daily min temp. (°C)	Mean daily solar rad. (MJ m^{-2} day^{-1})	Total monthly rainfall (mm)	Mean daily max temp. (°C)	Mean daily min temp. (°C)	Mean daily solar rad. (MJ m^{-2} day^{-1})	Total monthly rainfall (mm)	Mean daily max temp. (°C)	Mean daily min temp. (°C)	Mean daily solar rad. (MJ m^{-2} day^{-1})
Feb'07	64.0	28.3	17.0	16.0	64.0	27.1	15.5	20.1	41.0	33.6	17.0	23.2
Mar'07	193.5	25.1	15.2	15.0	193.5	24.4	13.4	15.5	61.4	29.9	15.4	17.7
Apr'07	82.5	23.6	12.9	13.5	18.0	22.3	11.1	12.0	26.9	27.5	12.5	14.9
May'07	5.0	24.3	11.8	13.4	1.2	21.9	6.7	12.5	0.0	25.7	7.1	14.7
Jun'07	40.0	20.6	9.0	10.5	42.9	19.3	6.9	10.2	28.0	21.6	5.6	12.1
July'07	0.0	22.1	8.9	12.7	0.1	21.1	6.3	12.0	0.1	22.7	4.7	14.2
Aug'07	23.0	23.4	9.6	12.6	18.9	21.7	6.3	11.1	1.3	25.5	7.0	15.9
Sep'07	68.0	24.3	12.8	11.8	60.6	24.3	10.9	11.8	13.0	29.5	12.9	16.6
Oct'07	256.5	21.0	12.2	11.0	237.6	20.5	10.8	10.8	125.9	24.7	12.9	14.8
Nov'07	285.5	22.5	13.4	13.6	160.8	22.7	12.4	14.0	92.2	27.7	14.4	19.3
Dec'07	175.0	24.0	14.7	16.2	136.6	23.8	13.4	15.7	100.5	29.1	15.1	22.6
Jan'08	287.5	25.1	16.1	14.6	196.1	24.3	14.6	11.8	146.6	29.9	16.4	21.9

TABLE 3. Summary of WUE data for selected South African indigenous tree species, as calculated from a mass-based ratio of biomass increment (stem wood or stem plus branch wood) over water-use.

Tree Species	1-yr Rainfall (mm)	1-yr Water -use (L)	Stem Volume Increment (cm³)	Total Volume Increment (cm³)	Ave. Wood Density (g cm⁻³)	Stem Mass Increment (g)	Total Mass Increment (g)	WUE (g stem wood / L water transpired)	WUE (g total wood / L water transpired)
Trema orientalis	1 437	8089	18426	25246	0.422	7776	10654	0.9612	1.3170
Celtis africana	1 165	8396	21855	37894	0.605	13222	22926	1.5748	2.7306
Podocarpus falcatus	1 165	6571	14659	18114	0.468	6861	8477	1.0441	1.2901
Ptaeroxylon obliquum	1 165	4407	8117	12011	0.716	5812	8600	1.3188	1.9514
Olea europaea subsp. *africana*	607	5223	1784	5875	0.916	1634	5382	0.3129	1.0304
Berchemia zeyheri	667	6103	12659	15200	0.807	10216	12267	1.6739	2.0099

Figures

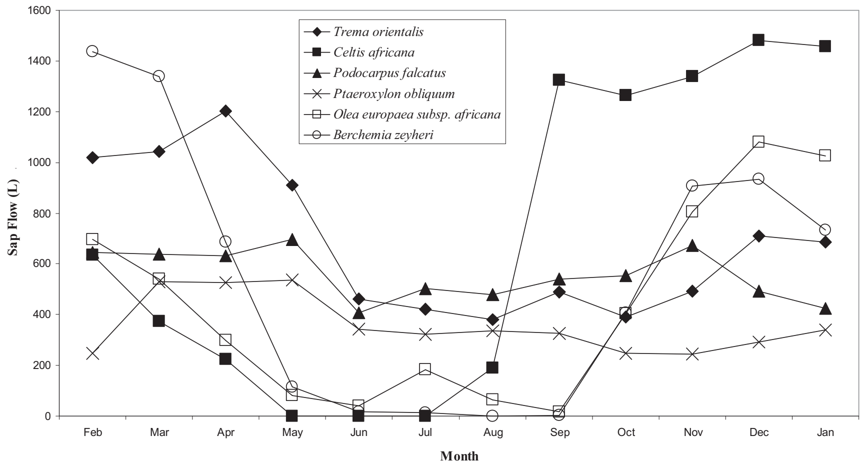

FIG 1. Monthly sap flow volumes (water-use) of selected South African indigenous tree species.

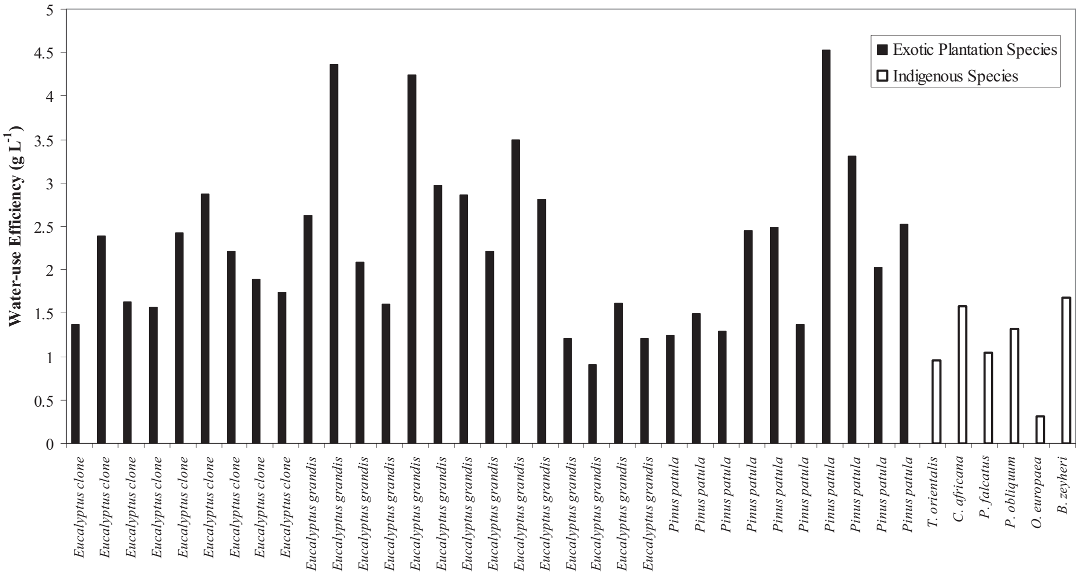

FIG 2. A comparison of water-use efficiency (stem mass increment per mass of water transpired) for exotic commercial plantation trees (Olbrich et al., 1996; Dye *et al*., 2001) and selected South African indigenous trees (last 6 bars).

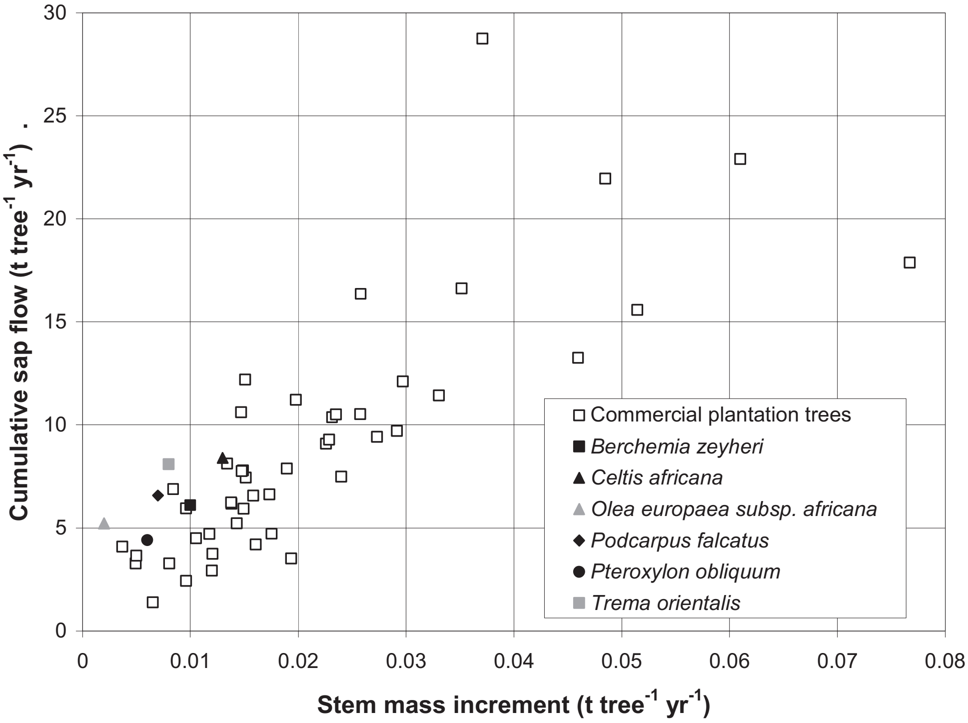

FIG 3. A comparison between 1-yr stem mass increment and 1-yr total sap flow, for exotic commercial plantation trees (Olbrich et al., 1996; Dye *et al*., 2001) and selected South African indigenous trees.