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A comparison of the biophysical and economic water-use efficiencies of indigenous and introduced forests in South Africa

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ABSTRACT

Water resources in many catchments in South Africa (SA) are over committed and water is projected to become scarcer. The impacts of plantation forestry on water resources in SA are well known and legislation limits further afforestation. Nevertheless demands for wood continue to grow. A challenge therefore is to increase the production of forest products within water constraints. This paper presents research into the economic and biophysical efficiencies with which indigenous and introduced tree-production systems in SA use water to produce harvestable biomass. Its purpose is to better inform resource allocations. Key findings are that: introduced plantations are more efficient at using water to produce harvestable biomass than indigenous species; the lower water-use efficiencies of indigenous species are due to slow growth rates and not high water-use rates; and the performance of indigenous forests improves when using the economic return per unit of water used – using the residual imputation approach to value the water – because of their lower production costs and higher product prices. Introduced plantations make up the majority of afforested land and total outputs in SA, however, therefore innovative mechanisms are needed to overcome barriers preventing the financing of indigenous forests. Possible financing mechanisms include the UN CDM and REDD programmes and tax breaks for superannuation funds.

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1. Introduction

Since the late 19th century South Africa's (SA) demand for timber has substantially exceeded availability from indigenous forests. The total area of indigenous forest is relatively low (approximately 3000 km², 0.1% of total area; Mucina and Rutherford, 2006) and mostly scattered in small patches widely distributed over the eastern and southern areas of SA. The annual harvestable yields generally do not exceed 2–3 tonnes per ha (Low and Rebelo, 1996; Midgley et al., 1997). To meet timber demands the area in SA planted to plantations of introduced *Pinus*, *Acacia* and *Eucalyptus* species now covers approximately 1.3 million ha (FSA, 2010). The industry, including support industries, contributes about 1% to South Africa's Gross Domestic Product and employs about 170,000 people (Chamberlain et al., 2005).

These large areas of introduced plantations, however, have also led to reductions in water yields from afforested catchments, as they use more water than the original grasslands or Fynbos¹ that

they replace (Dye, 1996; Scott et al., 2000). Since water resources in many catchments in SA are already over-committed (Department of Water Affairs and Forestry, 2004), early legislation introduced in 1972 to regulate the forest industry was refined in the South African National Water Act of 1998, declaring commercial afforestation as a stream-flow reduction activity (SFRA) or land use that may reduce the amount of water in rivers, and its availability to downstream users (Republic of South Africa, 1998). Under the new SFRA Water Use Licensing System the requirement for afforestation licences has limited further afforestation in areas where water resources are already committed.

The per capita (and total) demand for wood and wood products, however, is rapidly growing from a low baseline of about 69 kg yr⁻¹ – compared with 114 and 210 kg yr⁻¹ in Malaysia and the United Kingdom, respectively (WRI, 2005) – as the economy grows and as poverty is reduced (Crickmay and Associates, 2004a,b; LHA, 2004). The challenge is therefore to increase the production of forest products within these natural-resource constraints. A critical component of a strategy for meeting these increased demands is to improve the efficiency with which afforested areas use available water. In this regard, there is a widespread perception that indigenous tree species, in contrast to

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¹ Fynbos is the natural shrubland or heathland vegetation characteristic of the winter rainfall coastal and mountainous areas of the Western Cape, South Africa.

introduced *Pinus*, *Eucalyptus* and *Acacia* species, are efficient water users and should therefore be more widely planted. This perception appears to be based on the observation that indigenous trees are generally slow growers, and the belief that growth and water-use are broadly linked (Dye et al., 2008). However, tree water-use, and the total evapotranspiration (ET) from forests and woodlands, is technically difficult to measure, and so empirical evidence supporting the contention that indigenous trees and forests are more water efficient is scarce and indirect. In recent years, research has been solicited and funded by the Water Research Commission of South Africa (WRC, 2004), and undertaken by the Council for Scientific and Industrial Research (CSIR) in South Africa, to improve understanding of the biomass-growth and water-use rates of a wide selection of indigenous and introduced tree production systems to determine their biophysical and economic water-use efficiencies (WUE) (Dye et al., 2008). In this context, 'biophysical WUE' is defined as the quantity of biomass harvested and used for timber, pulp or fuelwood per unit of water evapotranspired ($\text{m}^3 \text{m}^{-3}$) and 'economic WUE' is the return attributable to the use of water ($\text{\$ m}^{-3}$) – in this case evapotranspired water – calculated as the present value of the total returns to production after subtracting all non-water related expenses, using the 'residual imputation approach' (Turner et al., 2004). Since the terminology for the technical concepts of WUE remains poorly defined (Perry, 2007) and in general relates to irrigation agriculture (Wallace, 2000; Clemmens et al., 2008; Evans and Sadler, 2008; Qureshi et al., 2010), the application of these concepts to rain-fed forestry are elaborated in Section 2.

The purposes of this paper are to report on the approach developed to determine the economic and biophysical WUE of indigenous and introduced tree-production systems and to present and comment on the key findings. Ultimately, it is expected that this research will inform the debate on the relative WUE of introduced and indigenous species and improve land and water allocations in water-stressed catchments of SA.

2. Economic and biophysical water-use efficiency

Water-use efficiency can be broadly defined to mean "maximising the returns from and minimising the environmental impacts of every megalitre (ML) of water used" (Hood, 2002). Such a concept is useful for informing different aspects of land and water resource management including reducing overall water usage and producing higher and/or better quality yields. Measuring and managing WUE in agricultural and forestry systems is therefore useful in promoting sustainable resource use.

Two measures of WUE from the literature on irrigation cropping systems which are relevant to informing water management in rainfed forestry are provided by Hood (2002): (1) crop/plantation WUE which measures the aboveground biomass produced for every ML of evapotranspiration (plant transpiration, wet canopy evaporation, soil evaporation) – also termed 'physical irrigation efficiency' (Burman et al., 1983); and (2) economic WUE which measures the net economic return per ML of water, estimated by subtracting the costs of all measured non-water inputs from the total per hectare returns to production (i.e., the residual return) and dividing by the average annual quantity of water evapotranspired per hectare. In this study, the WUE criteria are estimated using ET rates from stands of trees and not from irrigation water. Palmer et al. (2010) adopt the same approach for estimating grassland WUE in KwaZulu-Natal. The methods used to estimate these values are presented in Section 4.

A review of the literature on WUE reveals most research in this area has focused on agriculture (excluding forestry) and more particularly irrigation agriculture (e.g., Qureshi et al.,

2011; Speelman et al., 2008). In general, these studies investigate various measures of WUE for the purpose of improving the productivity and profitability of water use. Qureshi et al. (2011) provide a detailed analysis and discussion of biophysical and economic "irrigation water-use efficiencies" at different scales to better inform policy reform in the Murray–Darling Basin of Australia. Cai et al. (2001) investigated the relationships between physical efficiency and economic efficiency noting that the values of these measures may indicate different directions for water policy and investments in irrigation. The scale of the analysis of WUE has been highlighted as pivotal in these analyses. Seckler (1996) and Keller (1992), for example, show that being water-use efficient at the farm scale need not enhance economic efficiency at the basin scale largely because downstream re-use of the 'lost' water raises overall basin efficiency. Whether or not improved WUE at the farm or forest-stand scale translates into real water savings at a basin scale depends on hydrological systems within the basin and the landowner adoption rates of new technologies (see Ahmad et al., 2007). Others, including Tewari (2003), Nieuwoudt et al. (2004) and Moolman et al. (2006) have undertaken economic analyses of WUE and estimated economic returns from different agricultural activities, including forestry.

From the experiences and lessons presented above it is clear that comparing and contrasting the economic returns to water in agriculture and forestry systems is an appropriate way for assessing water-use and provides additional support to managers in the allocation of these scarce resources. This is particularly important for the forestry industry in South Africa where demand for timber is increasing but where water legislation has limited the further expansion of tree plantations in catchments with fully committed water supply.

3. Study sites

The selected introduced and indigenous forests² in this study represent the range of climatic conditions under which such systems grow in South Africa. These sites span a rainfall gradient from 730 to 1700 mm per year (Fig. 1) and include: (A) the De Hoek State Forest in Magoebaskloof in the Limpopo Province, comprising a stand of riparian indigenous Yellowwood trees (*Afrocarpus falcatus*, previously known as *Podocarpus falcatus*); (B) the Bushbuckridge and Skukuza areas outside of and within the Kruger National Park in southern Mpumalanga which are representative of semi-arid savanna vegetation; (C) a *Pinus patula* plantation in Swaziland; (D) numerous sites along a north–south rainfall gradient in KwaZulu-Natal and Mpumalanga provinces where *Eucalyptus* plantations are grown; and (E) the Knysna/George district in the southern Cape where 100,000 ha of pine and 60,500 ha of sub-tropical afro-temperate forest grow. The management regimes and harvested commodities of each system are described in this section and the site characteristics summarised in Table 1. The procedures for calculating the tree growth rates, standing and harvest volumes, ET rates and economic values are presented in Section 4.

3.1. Afro-temperate forests and pine plantations in the southern Cape of South Africa

The southern Cape indigenous and introduced forests occur on the coastal strip (altitude 190–300 m above sea level (m.a.s.l.)) between Mossel Bay in the west and Kareedouw in the east

² The FAO definition of a forest has been adopted and includes any land with greater than 10% cover by woody, perennial plants (FAO, 2003). It therefore includes forests, savannas and plantations.

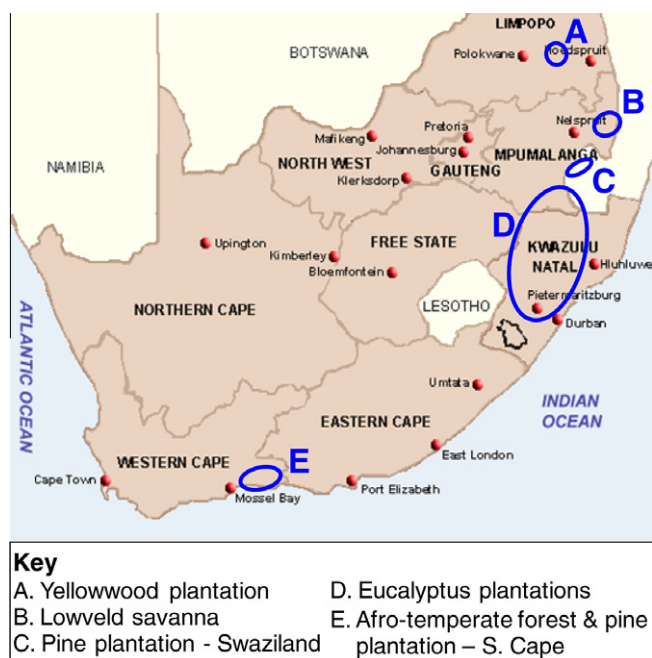


Fig. 1. General locations of the 18 plantations and forests along a rainfall gradient in South Africa.

(Fig. 1E). The afro-temperate forest at the study site in the Groenkop forest is approaching ecological equilibrium. It has a high standing biomass, a low mean annual increment and a stable composition of tree species (Geldenhuys, 1998). Dominant species include *Olea capensis* subsp. *macrocarpus*, *Podocarpus latifolius* and *A. falcatus* (Gush and Dye, 2004; Dye et al., 2008). *O. capensis* is the most common species and *Ocotea bullata* provides the most valuable timber (Geldenhuys, 1980). The forest is managed under the *senility criteria harvesting* yield regulation system (Seydack et al., 1990; Seydack, 1995) which combines forest rehabilitation with high-grade timber production by allowing trees to be harvested on a single-tree selection basis from 26% of the area (Geldenhuys, 1999; Gush and Dye, 2004). Also, the detrimental effects of tree

harvesting are minimised by: topping large trees before felling; using special extraction equipment to reduce soil compaction; and selectively planting seedlings of *A. falcatus* and *O. bullata*.

The main introduced plantations in the area and bordering the afro-temperate forests are *Pinus radiata* plantations, grown for timber. The management strategy of pine plantations grown for saw-log production involves: rotation lengths of 28–30 years; a planting density of 1111 stems per hectare; fertilising using inorganic fertilisers; controlling pests; intensive weeding in the first 3 years, pruning to a maximum height of 5 m, and three thinnings (FES, 2007).

3.2. Yellowwood tree plantation in De Hoek State Forest in Magoebaskloof, Limpopo Province, South Africa

A 2.5 ha stand of riparian Yellowwood trees (*A. falcatus*) was planted in a riparian zone within the De Hoek State Forest (altitude 857 m.a.s.l.) in the Magoebaskloof area of the northern Limpopo Province between October 1982 and December 1983 (Geldenhuys and von dem Bussche, 1997). The area forms a part of the Drakensberg escarpment and experiences a sub-tropical climate (Fig. 1A). The tree spacing is 3 m by 3 m (1111 stems ha⁻¹) and blanking (i.e., the replacement of dead trees) took place over the first 3 years. No thinning, weeding or fertilising has been performed, but competing understorey vegetation has been slashed regularly (Dye et al., 2008). The trees were planted in this area because of the warm temperatures, high rainfall, fertile soils and presumed year-round availability of soil water (Dye et al., 2008). The rotation length for this stand is expected to be 40 years.

3.3. The lowveld bioregion of the savanna biome, Kruger National Park and Bushbuckridge municipality, South Africa

Estimates of ET and tree growth were obtained at an experimental site situated 13 km west-southwest of Skukuza camp in the Kruger National Park. The site is semi-arid and hot (Table 1). A detailed site description has been published (Scholes et al., 2001). This analysis was confined to a ridge-top area characterised by sandy soils and dominated by the tree species *Combretum apiculatum*, *Sclerocarya birrea* and *Lannea schweinfurthii*. The lowveld bioregion of the savanna biome (Mucina and Rutherford, 2006) provides goods such as herbs, fruits, bushmeat, fuelwood, medici-

Table 1

Summary of the location and characteristics of site of each plantation and forest included in the analysis.

Location	Latitude longitude	Mean annual temperature (°C)	Mean annual precipitation (mm)	Soil form	Tree/forest type
Groenkop, southern Cape	S 33° 56' E 22° 33'	18	860	Lamotte/Kroonstad/Westleigh/Clovelley	Afro-temperate forest
Magoebaskloof	S 23° 50' E 30° 03'	19	1001	Tukulu	Plantation of <i>Afrocarpus falcatus</i>
KNP site near Skukuza	S 25° 01' E 31° 30'	22	570	Clovelley/Hutton/Glenrosa	Natural lowveld savanna
M1 Gembokfontein	S 26° 53' E 30° 53'	17.2	868	Hutton	<i>Eucalyptus grandis</i> plantation
M2 Windy Hill	S 29° 31' E 30° 33'	17.8	993	Inanda	<i>Eucalyptus grandis</i> plantation
M3 Kwambonambi	S 28° 39' E 32° 05'	21.2	1154	Fernwood	<i>Eucalyptus grandis</i> plantation
M4 Kia-Ora	S 30° 07' E 30° 08'	17.4	752	Hutton	<i>Eucalyptus grandis</i> plantation
M5 Tanhurst	S 30° 17' E 30° 26'	18.1	962	Oakleaf	<i>Eucalyptus grandis</i> plantation
M6 Baynesfield	S 20° 45' E 30° 21'	17.9	735	Hutton	<i>Eucalyptus grandis</i> plantation
M15 Palm ridge	S 28° 18' E 32° 15'	21.9	820	Grey Fernwood	<i>E. grandis</i> × <i>urophylla</i> plantation
M20 KT	S 28° 37' E 32° 09'	21.5	1224	Yellow Fernwood	<i>E. grandis</i> × <i>urophylla</i> plantation
M25 Futululu	S 28° 25' E 32° 14'	21.8	856	Yellow Fernwood	<i>E. grandis</i> × <i>urophylla</i> plantation
M29 Amangwe	S 28° 36' E 32° 06'	21.6	1104	Yellow Fernwood	<i>E. grandis</i> × <i>urophylla</i> plantation
M22 Bushlands	S 28° 06' E 32° 17'	21.9	754	Grey Fernwood	<i>E. grandis</i> × <i>camaldulensis</i> plantation
M17 Bushlands	S 28° 07' E 32° 16'	21.9	750	Yellow Fernwood	<i>E. grandis</i> × <i>tereticornis</i> plantation
Usutu, Swaziland	S 26° 25' E 31° 00'	1440	1124	Hutton/Clovelly	<i>Pinus patula</i> plantation

Sources: Information on the *Eucalyptus* plantations is from Smith et al. (2006); the soil information is from the 'soil classifications' report by the Soil Classification Working Group (1991); the details of the Yellowwood plantation in Magoebaskloof are from Geldenhuys and von dem Bussche (1997). The data for the Swaziland pine plantation are reported in (Dye, 2001); and the Groenkop site comprising the afrotemperate forest and pine plantation is described in detail by Dye et al. (2008).

nal plants, poles, and thatch grass for roofs. However, fuelwood is the only output considered in this study because it is the principle product harvested from savannas in this region. It is the primary energy source for 90% of rural households (Madubansia and Shackleton, 2007a,b), and reliable estimates of harvested quantities are available from the neighbouring Bushbuckridge municipality (Shackleton and Shackleton, 2000; Dovie et al., 2002; Ndengejeho, 2007).

Two fuelwood management systems have been investigated in this analysis. The first involves the existing traditional practice of directly harvesting fuelwood and the second involves an intensively managed sustainable fuelwood-production system that is an estimated 35% more productive than the unmanaged system. Since demand for fuelwood frequently exceeds supply in this region (Banks et al., 1996) the maximum harvest is limited to 90% and 98% of the annual regeneration rate of each system, respectively.

3.4. Pine plantation in Swaziland

A tree-growth trial was established within a 355 ha pine plantation in the Usutu Forest, Swaziland in 1981. The forest is located at an altitude of about 1400 m.a.s.l. with an MAP of 1750 mm (Fig. 1C). Further site characteristics are listed in Table 1. The pine stands were managed for pulpwood and therefore were not thinned or pruned and were harvested after only 15 years. All plots were intensively managed and received full weed control, fertilization, and pest control where necessary.

3.5. Eucalyptus plantations in KwaZulu-Natal, South Africa

Data from twelve *Eucalyptus* trial plantations situated within the provinces of KwaZulu-Natal and Mpumalanga in South Africa (Smith et al., 2006) were used to assess the WUE of commercial plantations of this genus. The trials were initiated and managed by the Institute of Commercial Forest Research, and covered a wide range of growing conditions and potential productivity (Table 1). The trials were managed for pulpwood, and consequently were planted at a density of 1667 stems per hectare, were not thinned or pruned, and were harvested after a relatively short rotation length of 7–15 years. All plots received full weed control, fertilization, and pest control where necessary.

4. Methods

A combination of direct sampling and simulation-modelling techniques was used to quantify the biomass accumulation and ET rates of the stands of trees for most of the forests and plantations investigated. These methods are described in Section 4.1. In some cases, the biophysical data were collected directly from forestry companies and the SA National Parks Board. The estimation procedures used to calculate the biophysical WUE criterion and the economic WUE criterion for each tree-production system are presented in Sections 4.1 and 4.2, respectively. The economic model is based on the Benefit-Cost-Analysis framework. The economic parameters values used to parameterise the economic model are derived from surveys of the relevant literature, stakeholders, and government data sources and are discussed in Section 4.2.

4.1. Estimating 'biophysical water-use efficiency'

The annual biophysical water-use efficiency of a forest or plantation (*BiophysicalWUE_t*) is defined as the quantity of biomass harvested and used for timber, pulp or fuelwood per unit of water evapotranspired (transpired by the trees, evaporated from wet

canopies and evaporated from the soil) from a homogenous area of forest/plantation and is calculated as:

$$\text{BiophysicalWUE}_t = \frac{h_t}{\text{ET}_t} \quad (1)$$

where, ET_t is the annual quantity of water used by the forest per hectare, measured as the annual rate of ET ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$) and h_t is the amount of biomass harvested and used for timber, pulp or fuelwood per hectare per year ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$).

The harvested products and ET rates depend on the species, growth rates, and the ways in which the forest/plantation systems are managed. These variables have been estimated for each of the systems under investigation using a combination of direct sampling and simulation modelling techniques. These methods are described below for each tree-production system in turn.

4.1.1. Afro-temperate forest and pine plantations of the southern Cape, South Africa

The annual ET rates over 20 years of the afro-temperate forest in the southern Cape was simulated using the Penman–Monteith (P–M) equation with a sub-model (Granier et al., 2000) accounting for variable canopy conductance (Dye et al., 2008). The P–M equation was used as it gave the best match (highest R^2 and slope closest to 1) of predicted to observed daily ET. The P–M equation was run using input weather data recorded at the nearby Saasveld weather station and verified against 18 days of spatially-averaged scintillometer measurements³ taken over three seasons. Mean annual volume growth of stems from the afro-temperate forest was estimated from long-term monitoring data in permanent sample plots located within a portion of the forest (Geldenhuys, 2005).

The 3-PG process model (Landsberg and Waring, 1997) was used to simulate the biomass accumulation of the *P. radiata* plantations. Structural and physiological features of this species are well described in the literature (e.g., McMurtrie et al., 1994). In addition, this model has also previously been used to simulate the growth of *P. patula* plantations in South Africa (Dye, 2001). Model simulations of ET were judged to be realistic when predicted leaf areas, diameters, heights and stand volumes matched data from yield tables and other sources for *P. radiata* in South Africa.

4.1.2. Yellowwood plantation, Magoebaskloof, Limpopo Province, South Africa

The estimates of ET for the entire Yellowwood plantation at Magoebaskloof were determined based on short-term seasonal measurements above the plantation using the Eddy Covariance (EC) technique. Total ET was determined on three separate occasions; namely in the late dry season (22–28 September, 2005), the wet season (9–15 February, 2006) and the dry season (23–30 August, 2006), for a total of 22 complete days of measured evaporation data. These measurements were combined with continuous sap flow measurements on a selection of individual trees within the plantation using the Heat Pulse Velocity (HPV) technique (Gush et al., 2009). The trees were selected following a stem diameter survey of the trees in the vicinity of the micrometeorological systems at the start of the first field campaign, and five sample trees were selected to each represent one of the five size classes of tree (Dye et al., 2008). Combining data from both measurement systems allowed estimation of the contribution of below-canopy ET towards the whole-stand ET. A P–M/Granier model was subsequently verified against the ET measured from the plantation

³ Three micro-meteorological techniques Scintillometry, Eddy Covariance, and the Bowen Ratio were in fact tested, and the most appropriate of these was the scintillometer (Dye et al., 2008).

canopy, and ET estimates extrapolated to a 12-month period corresponding to the period of sap flow measurements.

Geldenhuys and von dem Bussche (1997) reported on growth data recorded at the study site during October 1993 (11 years after planting), while additional growth survey data recorded during May 2001 (19 years after planting) were sourced from unpublished records at the holding company (Komatiland Forests). These data were combined with stem circumference and height data measured on 48 trees at the study site in August 2006. Based on a sample of *A. falcatus* trees in the southern Cape with diameters less than 40 cm, Geldenhuys (1983, pers. comm.) derived the following relationship (Eq. (2)) between single-tree stem diameter and stem volume:

$$V = 0.0000996 * DBH^{2.5} \quad (2)$$

where V is stem volume (m^3) and DBH is Diameter at Breast Height (cm). This equation was used to calculate average single-tree stem volumes at the times of the respective surveys, which were scaled up to plantation scale using the planting density. Growth trajectories were used to calculate changes in Periodic Mean Annual Increment (PMAI) values, i.e., the mean annual increment observed between growth surveys to derive a growth rate for the year of interest (2005/2006).

4.1.3. The lowveld bioregion of the savanna biome, Bushbuckridge municipality and southern Kruger National Park, South Africa

For the purposes of this long-term study, the ET rate of savanna vegetation in the lowveld bioregion was assumed to equal the average annual rainfall at the study site. This assumption was necessary because measuring and simulating the ET of savanna systems is made complex by fast changes in leaf area dynamics and soil water availability, spatially variable tree density and species composition, and significant herbivore influences. Additionally, soil–water storage and runoff ratios are relatively small in such arid sites. Although this assumption provides a reasonable approximation for the water use of relatively dense vegetation, it is likely to overestimate the ET at the study site (where vegetation cover is 70%), which means the final WUE estimate is conservative. The mean annual net primary production of the trees and shrubs for the semi-arid savanna vegetation type was estimated using the CENTURY 4.0 model (Parton et al., 1993) utilising weather and soil data from a flux tower and weather station (Scholes et al., 2001) located 100 m away. These generated data provided the basis for determining the quantity of fuelwood available for harvesting (see Section 4.2 and Supplementary material).

4.1.4. *P. patula* plantation in Swaziland

The growth of a *P. patula* plantation in Swaziland was monitored in five plots of differing tree densities (820, 950, 1116, 1333 and 1600 trees per hectare) where the row spacing was a constant 2.74 m in all plots but the within-row spacing of trees varied depending on the planting density. Regular annual growth measurements in each plot were performed over the trial period between 1981 and 1995 when the trees were clear-felled. The ET at this site was estimated from a detailed 3-PG simulation of the mean density plot (1116) (Dye, 2001). Model outputs suggested annual ET to be on average 94% of annual rainfall over 10 years.

4.1.5. *Eucalyptus* plantations in KwaZulu-Natal, South Africa

Water-use measurements of *Eucalyptus* plantations at the whole stand level (i.e., ET) are scarce and the few estimates that are available have been indirectly inferred from long-term catchment and soil–water balance measurements and from modelling studies (Dye et al., 2008). Such indirect estimates are potentially subject to numerous errors and may be imprecise. Therefore, as

in the case of the semi-arid savanna, the ET of the *Eucalyptus* tree-production systems was assumed equal to the mean annual rainfall. Tree growth data were available from two long-term trial series established to investigate stand density over a wide range of growing conditions and potential productivity (Dye et al., 2001).

4.2. Estimating 'economic water-use efficiency'

The valuation method used to estimate the economic value of water is the "residual imputation approach" (Young, 2005). This method calculates the value of water as the difference or "residual" between the total returns to production per hectare and the non-water related expenses per hectare (Turner et al., 2004). It is therefore assumed that this "residual value" is the returns to water and represents the amount the producer would be willing to pay for water and still cover input costs (Naeser and Bennett, 1998). The average value per ML is estimated by dividing the per-hectare residual value by the per-hectare quantity of water used.

Since the systems investigated in this study have diverse management regimes and experience benefits and costs at different times over rotations of varying duration, a long-run measure of the value of water is needed (i.e., that accounts for establishment costs and a normal rate of return on capital). To do this requires that the benefits and costs occurring at different times are discounted to present values using the appropriate discount rate. The cost-benefit analysis method provides a consistent, theoretically and empirically robust framework for doing this. To facilitate comparison, these values are "levelised" to constant unit values as described by Fane et al. (2003). Dividing the levelised residual value of water by the annual average ET rate gives the Economic WUE criterion, as defined in this paper. The economic model for determining the levelised average residual value of water (i.e., the *EconomicWUE_t*, US\$ m^{-3}) is expressed algebraically as:

$$EconomicWUE_t = \frac{\left[\sum_{t=0}^T [h_t \cdot p_h - vc_t] \cdot (1 + dr)^{-t} - EC \right] \cdot \left[\frac{dr}{(1 - (1 + dr)^{-T})} \right]}{ET_t} \quad (3)$$

where, ET_t is the annual evapotranspiration rate measured as the annual quantity of water transpired from trees and evaporated from the soil per hectare of homogenous forest/plantation ($m^3 ha^{-1} yr^{-1}$); h_t is the quantity of product harvested annually per homogenous hectare of forest/plantation – the units of which depend on the tree species and the outputs harvested (e.g., cubic metres of timber, tonnes of biomass for pulp, and kg of fuelwood); and p_h is the farm-gate price of the harvested product of each forest/plantation gross of harvest costs where the unit of measurement depends on the type of forest/plantation and product (US\$ m^{-3} or US\$ Mg^{-1}); vc_t represents the annual input costs including fertiliser, labour, herbicides, and harvest and transport costs (US\$ $ha^{-1} yr^{-1}$); T is the rotation length (years); EC is the cost of establishing a plantation (US\$ ha^{-1}) and dr is the discount rate (%).

In a strict sense, 'economic efficiency' is the maximum output produced from a given set of inputs and at minimum cost whatever the level of production. In this comparative static analysis of water use in a range of tree-production systems across South Africa, where empirical estimates of ET and growth rates from individual trees and stands of trees over time are generally not available, it has been necessary and sufficient to use time-average estimates for the values of WUE. Time averages are also adequate for the purposes of this study where the objective was not to determine optimal water allocations to maximise profits or minimise costs, but was to improve understanding and draw meaningful lessons of how different tree-production systems use water. In addition, the "residual return" criterion measures the return to water *plus all unmeasured inputs* and therefore can overstate the value of water

(Turner et al., 2004), therefore the results are tested in a sensitivity analysis.

Importantly, the economic model can be easily modified to account for payments for ecosystem services provided by forestry systems and the natural variability in many of the economic and biophysical variables. This requires that h_t , p_h , vc_t , and EC be expanded to include the additional outputs, prices, variable costs and establishment costs and that the probability distributions for the parameter values are known and included in the model, respectively.

4.2.1. Parameterising the economic model

Both primary and secondary economic data were used to parameterise the economic model and were collated from the literature and personal communication with landowners and managers of State and private forests and plantations. In general, the quantities and prices of all inputs and outputs were estimated as area-weighted averages over time periods of between 2 and 10 years, depending on the available data. In some cases, such as the fuel wood prices and quantities and some of the plantation input costs, the estimated values used in the model were determined as averages of numerous relevant site estimates. The details of the processes followed, and the data and sources used are provided in the [Supplementary material](#). All prices were adjusted to 2010 values using annual inflation data published by StatsSA (<http://www.statssa.gov.za/keyindicators/>). An exchange rate of ZAR7.3 per US dollar (US\$) was used to convert all prices from South African Rands to US\$; calculated as the mean of the 21-day monthly averages (<http://www.x-rates.com>). The economic parameter values used in the model are presented in [Table 2](#).

5. Results and discussion

5.1. Biophysical water-use efficiency estimates

The volume increment ($\text{m}^3 \text{ha}^{-1}$), harvested volume ($\text{m}^3 \text{ha}^{-1}$) and ET rates ($\text{m}^3 \text{ha}^{-1}$) for all tree-production systems investigated and determined from applying the methods described in [Section 4](#) are summarised in [Table 3](#). These biomass-growth data and water-use data were combined using [Eq. \(1\)](#) to determine the water-use efficiency of each forest/plantation as a whole [Table 3](#).

Table 2
Summary table of the economic parameter values (2010 US\$) for seven tree-production systems in South Africa.

Variable	Eq. (2) symbol	Unit	Southern Cape		Magoebaskloof	Bushbuckridge		Swaziland	KwaZulu-Natal
			Afro-temperate forest ^b	Pine timber plantation ^a	Yellowwood plantation ^b	Lowveld traditional harvesting ^c	Lowveld sustainable use ^c	Pine paper and pulp plantation ^a	<i>Eucalyptus</i> plantations ^a
Price of timber/fuelwood	p_h	US\$ m^{-3}	334	47.1	221	82.0	82.0	–	–
Price of pulp	p_h	US\$ Mg	–	–	–	–	–	31.5	31.5
Input cost	vc_t	US\$ $\text{ha}^{-1} \text{yr}^{-1}$	161	156	143	1.4	4.6	156.3	143.1
Annualised establishment cost	EC/T	US\$ $\text{ha}^{-1} \text{yr}^{-1}$	–	18	–	0.0	16.5	33.9	34.2–68.5
Establishment cost	EC	US\$ ha^{-1}	–	–	422	–	–	–	–
Harvest and transport cost	vc_t	US\$ $\text{ha}^{-1} \text{yr}^{-1}$	204	21	21	49.2	32.0	21.2	21.2

Sources: (a) the data for the introduced plantations are from Forestry Economic Services (FES, 2007); (b) the data for the afro-temperate forest and yellowwood plantation are from South African National Parks Board (Durrheim, 2007); (c) the data for the lowveld bioregion are from three studies in the Bushbuckridge municipality which borders the south-west border of the Kruger National Park (Shackleton and Shackleton, 2000; Dovie et al., 2002; Ndengejeho, 2007). The detailed explanations and data used to calculate these parameter values are provided in the [Supplementary material](#).

Note: All values are in 2010 US\$. Where necessary values have been inflated using inflation data published by Statistics SA (www.statssa.gov.za) and an exchange rate of US\$1 to ZAR7.3 has been used (www.x-rates.com).

Two features are noticeable in these numbers: the indigenous systems have the lowest values for biomass accumulation, and the overall water use of each of the indigenous systems is lower than most of the introduced plantations investigated. The way these two variables interact ultimately determines the biophysical WUE of a forest and depends on numerous and diverse factors including species physiology, plantation management, and site quality. The values for biophysical WUE estimated from these two variables are listed in [Table 4](#) (column 3).

Evidence from literature suggests that increases in productivity improve WUE (Binkley et al., 2004; Stape et al., 2004). This has also been shown for the forests investigated in this study ([Fig. 2](#)). The statistical significance of the relationship between Mean Annual Precipitation (MAP) and WUE, however, cannot be proved because of insufficient observations or data points. It is clear from the WUE values in [Table 4](#) (column 3) and plotted in [Fig. 2](#) that:

- (1) the *Eucalyptus* plantations are the most efficient at using water to produce harvestable wood volumes, at all levels of MAP;
- (2) the second most efficient are the pine plantations; and
- (3) the indigenous tree-based systems have the lowest biophysical water-use efficiencies of the systems investigated.

This finding suggests that slow-growing indigenous trees do not exhibit a high WUE. On closer inspection of these values, even though the WUE in each indigenous system was lower than the introduced plantation species, the overall water use of each indigenous system was also lower ([Table 3](#)). It is therefore concluded that the relatively lower WUE of the indigenous systems are more a consequence of slow growth rates as opposed to high water-use rates, indicating potential for low water-use forms of forestry using indigenous tree species. Gush and Dye (2009) report similar findings.

5.2. Economic water-use efficiency estimates

The estimated values for economic WUE of the selected forest are listed in [Table 4](#) (column 5). Plotting these economic WUE values against MAP ([Fig. 3](#)) reveals a similar positive relationship to that of the biophysical measure for WUE. However, a different pic-

Table 3

The biomass accumulation and yields and the water-use rates of 18 tree-production systems in South Africa.

Tree species	Plantation	Water evapotranspiration (m ³ ha ⁻¹ yr ⁻¹)	Volume increment (m ³ ha ⁻¹ yr ⁻¹)	Annual harvested volume (m ³ ha ⁻¹ yr ⁻¹)	Standing volume (m ³ ha ⁻¹)
<i>Eucalyptus</i> species ^a	M1 Gemsbokfontein	7911	21.0	20.6	189.4
	M2 Windy Hill	11,376	34.8	34.1	417.7
	M3 Kwambonambi	11,473	41.2	40.3	452.7
	M4 Kia-Ora	8514	24.0	23.5	264.1
	M5 Tanhurst	9801	27.9	27.3	306.6
	M6 Baynesfield	11,550	15.1	14.8	211.7
	M15 Palm Ridge	9284	22.8	22.4	250.9
	M20 KT	14,610	50.3	49.3	503.2
	M25 Futululu	7896	50.8	49.8	406.6
	M29 Amangwe	7287	35.3	34.6	247.1
	M22 Bushlands	8260	24.5	24.0	244.5
	M17 Bushlands	5782	32.3	31.7	226.1
	AVERAGE	9479	31.7	31.0	310.0
	<i>Pinus patula</i> ^c	Usutu, Swaziland	9160	28.3	27.72
Southern Cape		5641	11.5–12.5	7.6–10.6	322.0
<i>Pinus radiata</i> ^c	Southern Cape	9330	4.3	2.1–3.5	460.0
Afro-temperate forest ^{b,d}	Magoebaskloof	7160	4.1	–	92–138
<i>Afrocarpus falcatus</i> ^d	Kruger National Park	6210	0.3	0.3	9.1
Sandveld traditional management ^{d,e}	Kruger National Park	6210	0.4	0.4	12.2
Sandveld sustainable use ^{d,e}	Kruger National Park	6210	0.4	0.4	12.2

Source: (a) the biophysical parameter values for the 12 *Eucalyptus* plantations in KwaZulu-Natal Province are derived from Smith et al. (2006); (b) Durrheim (2007); (c) Forest Economic Services (FES, 2007); (d) Dye et al. (2007); (e) Wise et al. (2009).

Table 4

Estimates of the biophysical water-use efficiency, annual economic rent per hectare, and economic water-use efficiency of 18 tree-production systems in South Africa.

Tree species	Plantation/trial	Biophysical WUE (m ³ m ⁻³)	Economic rent (US\$ ha ⁻¹ yr ⁻¹)	Economic WUE (US\$ m ⁻³)
<i>Eucalyptus</i> species	M1 Gemsbokfontein	0.00261	\$9.6	\$0.002
	M2 Windy Hill	0.00300	\$121.8	\$0.014
	M3 Kwambonambi	0.00351	\$169.8	\$0.020
	M4 Kia-Ora	0.00276	\$39.5	\$0.006
	M5 Tanhurst	0.00279	\$99.8	\$0.013
	M6 Baynesfield	0.00128	\$4.0	\$0.0005
	M15 Palm Ridge	0.00241	\$61.3	\$0.009
	M20 KT	0.00338	\$275.7	\$0.024
	M25 Futululu	0.00631	\$290.1	\$0.045
	M29 Amangwe	0.00475	\$165.5	\$0.027
	M22 Bushlands	0.00290	\$74.7	\$0.012
	M17 Bushlands	0.00547	\$140.6	\$0.029
	AVERAGE	0.00343	\$121.0	\$0.017
	<i>Pinus patula</i>	Usutu, Swaziland	0.00303	\$124.0
<i>Pinus radiata</i>	Southern Cape	0.00133	\$32.5	\$0.009
Afro-temperate forest	Southern Cape	0.00028	\$77.2	\$0.019
<i>Afrocarpus falcatus</i>	Magoebaskloof	0.00057	\$45.0	\$0.015
Sandveld traditional management	Kruger National Park	0.00004	\$3.7	\$0.001
Sandveld sustainable use	Kruger National Park	0.00006	\$7.6	\$0.002

ture exists in terms of the relative water-use efficiencies of the various tree systems investigated.

Based on the economic WUE criterion, the indigenous afro-temperate forest ranks higher than all the other systems investigated except for the extremely productive, short-rotation (8, 7 and 7 years, respectively) *Eucalyptus* plantations at Futululu, Amange, and M17 Bushlands and the *Eucalyptus* plantation at M20 KT where the MAP is double that of the southern Cape (Fig. 3A). The relatively good performance of the afro-temperate forest is likely due to the fact that this system incurs no establishment costs and because of the high value of the fully-mature timber that is harvested.

The other indigenous tree system grown for timber is the Yellowwood stand in Magoebaskloof. The performance of this system dramatically improves based on the economic measure for WUE rather than the biophysical measure due to the high value of its timber relative to prices received for the wood from the eucalyptus and pine plantations. The Yellowwood plantation does not perform as well as the afro-temperate forest when measured in terms of its economic WUE, however, because: (1) a lower timber price is assumed, (2) it incurs large upfront establishment costs and (3) a single return is received only after 40 years and so is heavily discounted.

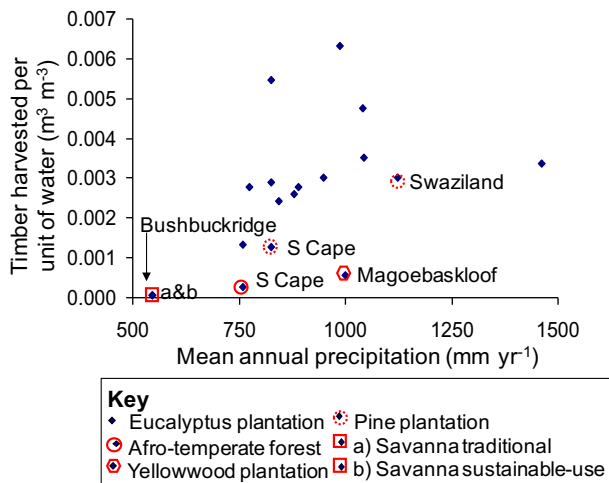


Fig. 2. The relationship between biophysical water-use efficiency (harvested wood volumes per cubic meter of water) and mean annual precipitation along a rainfall gradient in South Africa.

The ranking of the remaining systems is not easily determined from the few observations available. Initial indications from these limited data are that the pine plantations have higher economic water-use efficiencies than *Eucalyptus* plantations at low MAP, but that this difference becomes negligible as MAP increases. The economic WUE of the semi-arid savanna seems to be competitive with the pine and *Eucalyptus* plantations at low MAP, (Fig. 3A and B).

The limited data set has precluded a comprehensive comparison of within-site WUE of the indigenous and introduced systems along the entire rainfall gradient. The only within-site comparison possible is the pine and afro-temperate forests in the southern Cape region. On a per hectare basis, the afro-temperate forest is 2.4 times more profitable than the pine plantation (Table 4, column 4), with the former generating average annual returns of US\$77.2 ha⁻¹ compared with US\$32.5 ha⁻¹ for the latter. When measured in terms of economic WUE, however, this difference decreases from 2.4 to 2.1 times. This decrease in the relative profitability of the two systems is because the pine plantations are more efficient at using water to generate the volume of harvestable timber than indigenous trees. In other words, the larger profitabil-

ity of the indigenous forest is due to the high price received for its timber and not because it is necessarily more productive or cost-effective.

Although the afro-temperate forest is up to 2.4 times more profitable than the pine plantation, the maximum annual harvestable area of the former is only 0.9% of the entire area of the natural forest (i.e., 560 ha of 60,500 ha). There are therefore no opportunities to exploit this higher per-hectare profitability.

The sensitivity of the economic performances of the afro-temperate forest and Yellowwood plantation relative to the rest of the systems is tested for a 'pessimistic' scenario. The pessimistic scenario represents the economic performances of the two timber-producing indigenous systems after reducing their output prices by 10%. A pessimistic scenario is tested because the observed variability in both the input and output prices of the indigenous systems are skewed to their upper and lower values, respectively (i.e., the median values are higher and lower than the means, respectively (see Supplementary material)).

The absolute ranking of these two indigenous systems are clearly sensitive to a reduction in timber prices, particularly the afro-temperate forest (compare Fig. 3A and B). This is because of the small contribution of the residual inputs to the total output and the lack of reliable ET and productivity data and information on economic input and output quantities and prices. Notwithstanding the drop in the ranking of both these systems their performances are still higher using the economic WUE criterion than the biophysical measure for WUE.

6. Conclusions

This paper presents the findings of research into the relative economic and biophysical efficiencies with which a range of indigenous and introduced tree-production systems in South Africa use water to produce harvestable biomass with the purpose of improving land and water allocations.

The introduced eucalyptus and pine plantations were found to be more efficient at using water to produce timber or pulp than the indigenous afro-temperate forests and Yellowwood species. Indigenous species, however, possess an advantage over commercial species in their lower overall water use and lower streamflow reduction impacts. The lower water-use efficiencies of indigenous species relative to introduced species are therefore more a consequence of slow growth rates as opposed to high water-use rates.

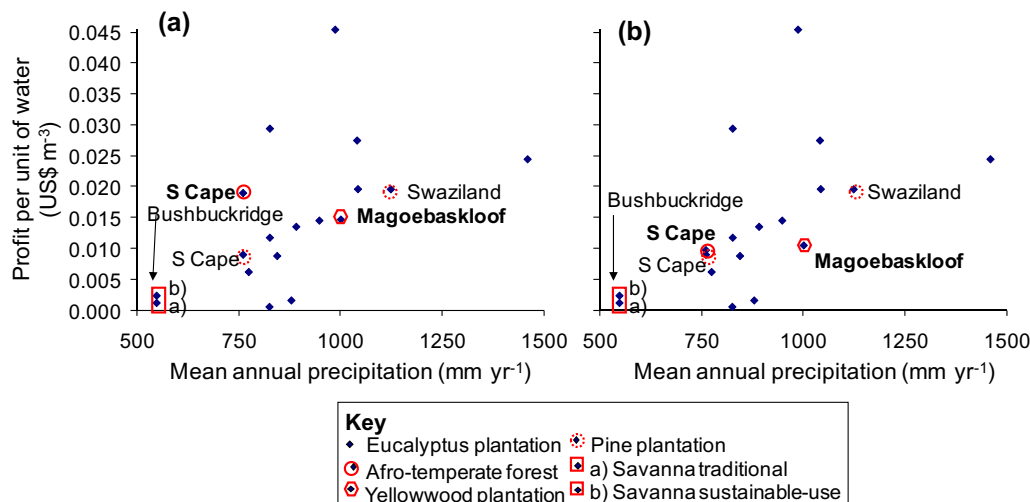


Fig. 3. The relationship between economic water-use efficiency (residual economic return per unit of water used (2010 US\$ m⁻³)) and mean annual precipitation along a rainfall gradient in South Africa for (a) base-case parameter values and (b) a pessimistic scenario for the indigenous systems using lower timber prices.

The WUE of the indigenous systems relative to introduced species improves when measured in terms of their economic WUE compared with their biophysical WUE; where economic WUE is measured as the return to water plus all unmeasured inputs (i.e., the residual return). This is particularly the case at low mean annual precipitation. The improved performance of these systems is because of their relatively low costs (not intensively managed) and higher product prices. This finding is also robust to changes in assumptions about input and output prices (i.e., they perform better based on an economic measure for WUE rather than a biophysical measure even if their ranking may change with changes in assumptions).

Two additional factors not accounted for in this study, which will improve the relative economic performances of the indigenous systems, are that these systems provide numerous, valuable use and non-use benefits to society in the form of ecosystem services (e.g., aesthetic, bequest, and carbon sequestration) and many potentially large downstream economic benefits from improving streamflows (Ring et al., 2010).

The fact that introduced plantations predominate in SA and that few indigenous plantations are being established means that innovative policy mechanisms, focused R&D, and appropriate institutions are urgently required to overcome the investment and information barriers to financing slow growth indigenous forests and plantations. Some market-based mechanisms to incentivise the flow of financial investments into slow-growth, long-term indigenous plantations might involve the introduction of tax benefits for superannuation funds to invest in such long-term projects (Low et al., 2010) and investigating the possibilities of 'payments for ecosystem services' under the UN-REDD programme ("Reducing Emissions from Deforestation and Forest Degradation") (Chhatre and Agrawal, 2009) or in carbon-sequestration projects under the CDM (van Kooten and Sohngen, 2007; Corbera et al., 2009).

The reliability of the economic results and confidence in using these findings to inform the development of management and policy depend on the quality of the information and data used to parameterise the model. These data are limited, particularly in the indigenous systems. An essential component of future initiatives to promote the adoption of indigenous tree-farming systems, therefore, is the development of a dedicated, long-term research agenda involving: empirical and modelling capabilities that focus on measuring the biomass-growth and water-use rates of a wide selection of indigenous and introduced tree production systems; accurately recording the economic costs and benefits of growing and harvesting indigenous forest/plantation systems; and quantifying the non-market, direct and indirect use and non-use benefits and improved downstream flows.

Comparing the range of economic WUE values for the tree-production systems estimated in this study (US\$0.001 to US\$0.045 m⁻³) with a conservative estimate of the opportunity cost of the water of \$0.06 m⁻³ estimated as the user-weighted average of the recovery costs incurred by downstream rural and urban users of water (de Lange and Kleynhans, 2008) brings into question whether the growing of plantations in the upper reaches of catchments is an appropriate use of scarce water resources. Answering this question requires the estimation of marginal economic values of water in forestry, which is data intensive and reinforces our recommendation for further investment in long-term research programmes in this area.

Finally, due to the low number of observations and the lack of economic data, the results presented should be considered exploratory and interpreted with caution. Although the general trends in the performances of the different tree-production systems based on their water-use efficiencies are robust to changes in the input data and parameter assumptions, their individual

rankings are not. This reinforces the need for additional research in this area.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2011.05.021.

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