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Review Article

Eucalyptus and Water Use in South Africa

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The *Eucalyptus* genus yields high rates of productivity and can be grown across a wide range of site types and climates for products such as pulp, fuelwood, or construction lumber. In addition, many eucalypts have the ability to coppice, making this genus an ideal candidate for use as a biofuel feedstock. However, the water use of *Eucalyptus* is a controversial issue, and the impacts of these fast-growing trees on water resources are well documented. Regardless, the demand for wood products and water continues to rise, providing a challenge to increase the productivity of forest plantations within water constraints. This is of particular relevance for water-limited countries such as South Africa which relies on exotic plantations to meet its timber needs. Research results from water use studies in South Africa are well documented and legislation restrictions limit further afforestation. This paper outlines techniques used to quantify the water use of eucalypt plantations and provides recommendations on where to focus future research efforts. Greater insights into the water use efficiency of clonal material are needed, as certain eucalypt clones show fast growth and low water use. To better understand water use efficiency, estimates should be combined with monitoring of stand canopy structure and measurements of physiological processes.

1. Introduction

Eucalyptus is the most widely planted hardwood genus in the world, covering more than 19 million hectares, with growth rates that routinely exceed 35 $\mathrm{m}^3\,\mathrm{ha}^{-1}\,\mathrm{year}^{-1}$ [1, 2]. These fast-growing plantations can be grown under a range of different climates for products that include pulp and paper, charcoal, fuelwood, and solid wood products such as poles, furniture, and timber construction. Given their fast growth rates and coppicing ability, eucalypts have also been identified as potential feedstocks for lignocellulosic biofuels. Being endemic to Australia, southeast Asia, and the Pacific, eucalypts are grown mainly as exotic species. Consequently, there is much concern about their water consumption, from many countries around the world [3–7].

One such country is South Africa, which relies heavily on plantations of exotic forestry species, particularly *Eucalyptus*, to meet its timber needs. South Africa is a water-limited country with an average annual rainfall of 560 $\mathrm{mm\,year}^{-1}$, which results in fierce competition for this limited resource [5]. Concerns over the effects of exotic plantations on South African streamflow and catchment water yields led to the establishment of a network of long-term paired catchment experiments in the major forestry areas of the country. These experiments were set up as early as 1937, and since then, have been supplemented by a wide variety of process studies comparing transpiration or evapotranspiration from forest, grassland, and other vegetation types. Information from these studies and the paired catchment experiments have been used to calibrate catchment models that have provided estimates of the hydrological impacts of forest plantations. As a result, the impacts of plantation forestry on water resources are well documented and legislation restrictions limit further afforestation.

Nevertheless, demand for wood, water, and energy continues to grow, providing a challenge to increase the productivity of forest plantations within water constraints. *Eucalyptus* species managed as short-rotation crops for bioenergy are of increasing interest in many parts of the world. In countries where eucalypts are introduced species, there is a need to understand key environmental issues, for example, water use, related to the management and growth of these trees. One way in which information needs can be identified and prioritized is to draw on the knowledge and experience gained from decades of water research in South Africa. Research into water use of South African timber plantations commenced in 1937; the historical nature of the data collected, the length of record, and the range of sites involved make the experiments unique and invaluable [8].

The objective of this paper is to provide a comprehensive synthesis of the available South African literature on the effects of eucalypt planting on water resources and to produce new insights into future research needs. This paper is organized into five main sections as follows:

(i) background to South African forestry and limited water resources,
(ii) techniques used to measure and model water use,
(iii) methods for determining water use efficiency,
(iv) current South African legislation, and
(v) future considerations, including a new research focus and tree-based bioenergy feedstocks.

2. South African Forestry and Limited Water Resources

South Africa has limited indigenous timber-producing forests. The first plantations of exotic trees, mainly pine and eucalypts, were established in the country in 1875 after recognizing that demand for timber had exceeded the supply available from indigenous forests. These exotic species were preferred for afforestation because none of the indigenous tree species which yield useful timber grew at rates considered profitable [9]. There has since been a steady expansion in the total area of forest plantations, culminating in 1.2 million hectares (1.1% of South African land area), of which 515,000 ha are planted to eucalypts [10]. This genus is grown predominantly for pulpwood and mining timber over a normal rotation length of seven to ten years [11]. Productivity from these plantations is relatively high and ranges from 10 to 68 m^3 ha^{-1} yr^{-1}.

Plantations of exotic species were established in the higher-rainfall (>700 mm) regions of the country, coinciding with a large proportion of the surface water resources which emanate from relatively small but important catchment areas concentrated along east- and south-facing escarpments and mountain slopes [12–14]. The dominant vegetation in many of these areas was originally montane grassland and fynbos (macchia) shrublands. Annual evapotranspiration rates of this indigenous vegetation range from 700 to 900 mm [15]. This indigenous vegetation has relatively shallow root systems and is seasonally dormant, resulting in limited evapotranspiration over the dry season [12, 15]. In strong contrast, plantation forests are characterized by deep root systems and tall, dense, evergreen canopies that maintain a relatively high leaf area index over the entire year [14, 16]. Evapotranspiration from established forest plantations is commonly in the range of 1100–1200 mm and is limited by rainfall available on the site [14]. Numerous local and international studies have indicated conclusively that forest plantations established in former natural forests, grasslands, or shrubland areas consume more water than the baseline vegetation, reducing water yield (streamflow) as a result [8, 13, 14, 17–20]. Concerns over the effects of these forest plantations on streamflows and catchment water yields arose as far back as 1915 and were thoroughly debated during the Empire Forestry Conference that took place in South Africa in 1935 [14]. A decision taken at this conference led to the establishment of a network of long-term paired catchment experiments in various catchments located in the major forestry areas of South Africa [14].

3. Techniques Used to Measure and Model Water Use

A range of techniques has been used to measure and model water use of South African forest plantations, across a range of temporal and spatial scales. These include paired catchment experiments, micrometeorological techniques, sapflow estimates using heat pulse velocity, modeling efforts, and remote sensing estimates of stand scale water use. Each of these techniques is discussed in turn; pertinent results are presented, and the short-comings of each method have been highlighted.

3.1. Paired Catchment Experiments

3.1. Paired Catchment Experiments. The paired catchment method involves the long-term monitoring of streamflow from pairs of catchments before and after a major vegetation change in one of them [8]. Van Lill et al. [21] reported on results of a paired catchment experiment with *E. grandis* versus natural grass cover on the eastern escarpment of South Africa. Afforestation with *E. grandis* exerted an observable influence from the third year after planting, with a maximum apparent reduction in flow between 300 and 380 mm $year^{-1}$, and with maximum reductions in seasonal flow of about 200–260 mm $year^{-1}$ in summer and 100–130 mm $year^{-1}$ in winter [21].

Catchment experiments have shown that eucalypts cause a faster reduction in streamflow compared to afforestation with pines [13]. Further, these effects were more marked for eucalypts (90–100% water reduction) than with pines (40–60% reductions in the first eight years or so after treatment), but Smith and Scott [22] suggested these differences may diminish as the pine stands become well-established. Streamflow reduction was significant from the third year after planting eucalypts, for both the wet and dry seasons, and the stream dried up completely in the ninth year after planting [13]. After afforestation with pines, reductions in total and wet season streamflow became significant in the fourth year and stopped flowing completely in the twelfth year [13]. Analyses showed peak reductions of 470 mm $year^{-1}$ for eucalypts in the seventh and ninth years, both particularly wet years [13]. The highest estimated flow reduction due to pine was 257 mm, recorded in the twentieth year of the rotation [13]. These finding were verified by a study performed by Scott et al. [8] who reported peak reductions in streamflow between 5 and 10 years after planting eucalypts, and between 10 and 20 years after planting with pines, with the size of the reductions being limited primarily by water availability. In analyses presented by Scott and Smith [18], reduction in annual streamflow due to pine, averaged over the first eight years after afforestation, was 47 mm (between 35 and 119 ha were afforested). In comparison, eucalypts reduced streamflow by 239 mm (over an afforestation range of 25–40 ha). In the case of the pines, between 82 and 100% of the catchment area was afforested; in the case of the eucalypts, entire catchments (i.e., 100%) were afforested.

In addition to afforestation effects on total streamflow, an important consideration is the effect on low flows, defined by Scott and Smith [18] as the driest three months of an average year, or as those monthly flows below the 75th percentile level. At the low flow time of the year during the dry period immediately prior to the rainy season, a reliable water supply is most critical for downstream water users [18]. Consequently, the effect on low flows may be more important than the overall impacts on streamflow [22]. Using the paired catchment approach to investigate low flows in five catchments in the winter and summer rainfall regions of South Africa, Smith and Scott [22] found afforestation significantly affected low flows in all five catchment experiments, with flows being reduced by up to 100% in some cases. The low flows in catchments planted with eucalypts showed a significant response to treatment from the third year after afforestation, whereas the catchments planted with pines only responded from the fifth year onwards [22].

Streamflow reductions are very variable from year to year, being a function of the following factors.

(i) Water availability (see [13, 17, 18]). According to Scott et al. [8], the most important determinant of flow reductions is water availability, where wet catchments with high water availability have the highest flow reductions. Conversely, low water availability can lead to bigger relative reductions; for example, one catchment planted to eucalypts reached 100% reduction in the fourth year of the rotation under a dry cycle.

(ii) Species selection and extent of afforestation [8].

(iii) Plantation age or growth rate (see [8, 18]). Smith and Scott [22] suggested that faster growth rates of eucalypts compared to pines in the first eight years after planting may explain their earlier and greater impact on low flows. Similarly, Bosch and Hewlett [17] stated that decreases in water yield following afforestation seem proportional to the growth rate of the stand, while gains in water yield after clearfelling diminish in proportion to the rate of recovery of the vegetation.

(iv) Rotation length. Mathematical models developed by Scott and Smith [18] indicated that the longer the rotation, the greater the mean impact of the crop and the lower the frequency of "recharge opportunities" (periods after clearfelling when evapotranspiration losses would be low). These models predicted that flow reductions caused by pines grown for sawlogs (on a 30-year rotation) were likely to be similar to those caused by a shorter rotation (8 to 10 years) eucalypt crop.

Whilst these paired catchment experiments confirmed a decline in streamflow following the establishment of forest plantations, Dye and Olbrich [12] and Gush et al. [16] cautioned that results cannot be extrapolated to other areas with confidence because of the lack of climatic representativeness. The research catchments studied have a mean annual precipitation greater than 1100 mm, whereas 63% of all afforestation in South Africa receives less than 900 mm per year [16]. In addition, in the studies cited by Smith and Scott [22], tree seedlings were planted into shallowly prepared pits without fertilization in contrast to typical forestry practice which involves intensive site preparation, and in some cases, fertilizer application to boost early growth. Such establishment practices are likely to cause earlier reductions of low flows from the afforested catchments because the site is fully exploited by the trees sooner [22]. Further, in the study of Scott and Lesch [13], two entire catchments were afforested, including the riparian zones, to indicate the potential effects of afforestation. However, under current forestry law in South Africa, riparian zones are not planted but are kept open under indigenous vegetation for soil and water conservation, and seldom would more than 75% of a single large catchment be afforested. Scott et al. [8] suggested replicating catchment experiments with different species, at different sites, and over different time periods, as results from a single catchment and climatic pattern cannot provide proper understanding of how responses may vary under different conditions. However, Hewlett and Pienaar [23] stated that the paired catchment approach, while powerful, is also costly and time-consuming.

Findings and recommendations emanating from the paired catchment experiments led to regulation of new afforestation to protect water supplies. In 1972, legislation was introduced that required timber growers to apply for permits (afforestation permit system) to establish new commercial plantations [20, 24]. These applications became mandatory and were granted or refused based on an assessment of the expected impact of plantations on water yields from the catchment areas [5].

There was thus a need for a model that could be used as a guideline for decision-making and planning regarding afforestation effects and permit allocations. Scott and Smith [18] developed mathematical models, using age as a predictor variable, to provide estimates of reductions in low flow and total flow resulting from pine and eucalypt plantations on a regional and national scale. Scott et al. [8] suggested adding environmental drivers such as rainfall, temperature, soil depth, or tree rooting in addition to using age as a predictor variable to enable explanation of observed variation. However, because of the lack of climatic representativeness, these models remain empirical and extrapolation outside the conditions encountered could be misleading.

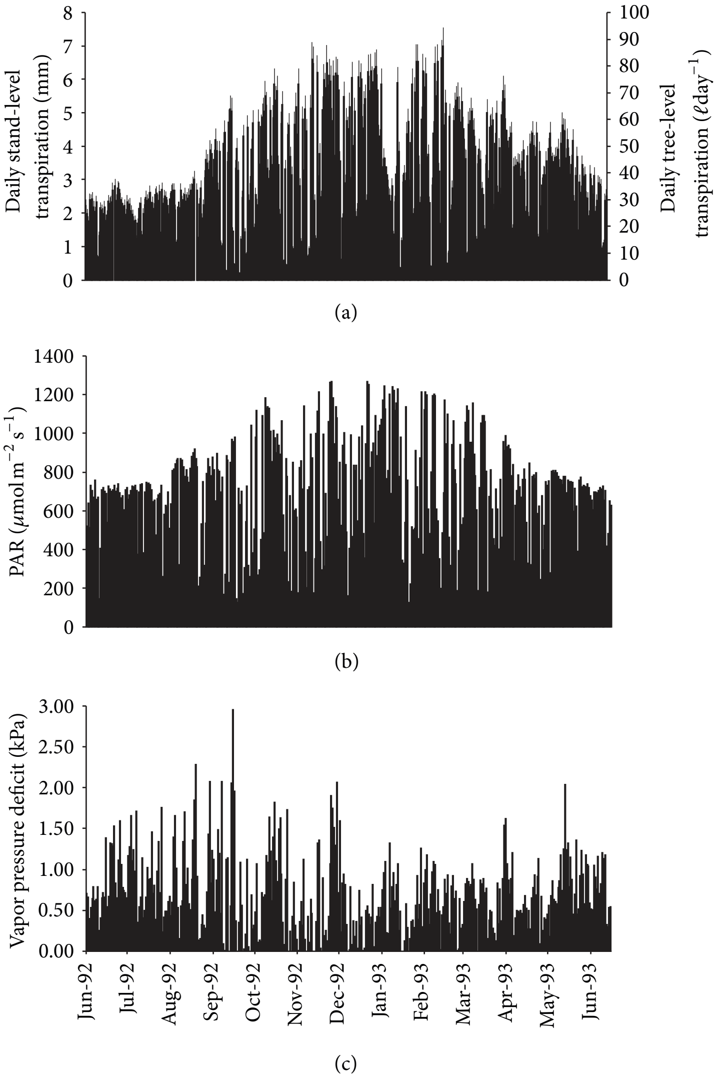

Figure 1: Mean daily transpiration of three-year-old *E. grandis* trees (a), photosynthetically active radiation (PAR) (b), and daytime (6 am–6 pm) vapor pressure deficit (c) for the period June 1992 to June 1993 (after Dye [25]; Dye et al. [26]).

3.2. Sapflow Measurements and Micrometeorological Techniques. Since the mid 1980s, the paired catchment experiments were supplemented by a variety of process-based studies, where transpiration or evapotranspiration were measured above forest, grassland, and other vegetation types, using heat pulse and micrometeorological techniques [14]. Transpiration (sapflow) rates measured using the heat pulse velocity technique have been verified in 3- and 16-year-old *E. grandis* trees [27]. Sapflow rates exhibit distinct seasonal patterns, where mid-summer values are characteristically highest, due to long day lengths and high vapor pressure deficit (VPD) associated with higher temperatures [28]. In contrast, winter sap flow rates were much reduced, not only by day length and VPD, but also by soil water deficits [28]. One of the mechanisms trees use to avoid drought conditions is stomatal closure, either in response to increasing VPD or soil water deficit [29, 30]. Closure of stomata to maintain leaf water potential above a critical threshold protects the xylem from damage by cavitation and embolism [31].

Transpiration from *Eucalyptus* trees in South Africa has been shown to be mainly a function of VPD and photosynthetically active radiation [12, 32]. Evidence of this is seen in Figure 1, where peak daily water use of three-year-old *E. grandis* exceeded 90 ℓ day^{-1} (7.0 mm day^{-1}) on hot dry days in midsummer and then declined during the fall as temperatures decreased and the photoperiod shortened. Average daily water use was approximately 30 ℓ day^{-1} (2.2 mm day^{-1}) during the 1992 winter but rose markedly in the spring in response to increased VPD [25]. Median daily sapflows in stands of *E. grandis* × *camaldulensis* hybrid clones covering a wide range in age (1.5–7.0 years) and site growth potential ranged from approximately 30 to 64 ℓ per day for trees growing on more productive sites, and from 15 to 34 ℓ per day for the less productive sites [33].

Dye [25] carried out sapflow studies at two field sites on three- and nine-year-old *E. grandis* trees subjected to soil drying by laying plastic sheeting on the ground to prevent soil water recharge. There was no indication that water use declined as a result of increasing soil water deficits. Dye [25] attributed this to the ability of the three-year-old trees to abstract soil water to a depth of at least 8 m, whereas nine-year-old trees obtained most of their water from depths below this level (deep drilling revealed live roots at 28 m below the surface). During dry periods, deep-rooted eucalypts are able to maintain transpiration at rates which enable the trees to function, by accessing water stored in the soil profile [34]. As available soil water is recognized as the main factor influencing the growth of commercial plantations in southern Africa [35, 36], a crucial question is whether water stored in the soil profile can be recharged during continuous *Eucalyptus* cropping, particularly in short-rotation unthinned plantations grown for pulp or bioenergy where leaf area index (and hence water use) remains high throughout the rotation [25]. Leaf area index is a key determinant of plantation water use [37–39].

Successive rotations of demanding species such as *E. grandis* may deplete soil water reserves, leading to increased soil water deficits and declining growth yields [26, 36]. In the paired catchment experiments studied by Scott and Lesch [13], eucalypts were clearfelled when 16 years old but full perennial streamflow did not return until five years later. This lag in streamflow recovery was attributed to the abstraction and desiccation of deep soil-water stores by the eucalypts which had to be replenished before the streams could return to normal behavior [13]. Greater understanding of the long-term water balance of eucalypt plantations is therefore required to assess the sustainability of continuous eucalypt cropping and evaluate what management practices can be adopted to minimize growth losses [26].

In addition to sapflow studies, micrometeorological techniques such as the Bowen ratio and eddy correlation have been investigated; however, these are less suited to *Eucalyptus* measurements as they require a structure to gain access to the foliage or to serve as a platform for instrumentation mounted above the canopy, which is made difficult by the height of the trees. In addition, leaf-based techniques such as porometry require adequate canopy sampling to allow estimation of whole-tree transpiration rates, and micrometeorological methods have theoretical constraints that are difficult to satisfy in undulating, discontinuous forest terrain [27].

An additional drawback of micrometeorological techniques and sapflow measurements is the expense, both in terms of equipment and time [28]. Sustaining high-quality sapflow measurements by the heat pulse technique over long periods of time is difficult as equipment malfunctions or is stolen, probes can become corroded by gum, or sample trees can be felled accidentally. There is limited ability to extrapolate results from relatively few research areas to the entire forestry region [28]. In addition, growth and water use is especially sensitive to soil water availability, but this is often impractical to measure because of deep rooting depths, highly variable depth to bedrock, and uncertainty over lateral soil water flow [28].

3.3. Modeling Efforts. Another assessment tool used to determine the impact of commercial afforestation on South African water resources was the ACRU (Agricultural Catchments Research Unit) model [44], which simulates streamflow, total evaporation, and land cover/management impacts on water resources at a daily time step [45]. Model inputs include daily rainfall and other climatic data, catchment characteristics such as catchment area, altitude, vegetation/land cover, and soil information. ACRU model processes include infiltration, evapotranspiration, reservoir storage, surface runoff, and plant growth. The hydrology component of the model utilises a multilayer soil water budget to calculate evapotranspiration. Jewitt and Schulze [45] performed a verification of the ACRU model by comparing simulated and observed streamflow at three forested catchment locations across a range of catchment sizes, forest species, and plantation age. The ACRU model performed acceptably at most sites, but Jewitt and Schulze [45] encountered problems related to temporal distribution of streamflow. Similarly, in another ACRU model verification study, Gush et al. [16] showed that mean annual streamflow reductions resulting from afforestation were satisfactorily simulated for most of the long-term research catchments. However, model predictions for dryer regions or those with winter rainfall were poor, and Gush et al. [16] concluded that the model could not account for the full storage capacity of soils and the year-to-year carryover of water storage or usage. Gush et al. [16] cautioned that in these types of situations where forest hydrology is less well understood, there is increased risk of erroneous predictions.

3.4. Remote Sensing Techniques. Remote sensing techniques using satellite imagery have successfully been used to estimate evapotranspiration across a range of spatial scales [46–48]. These techniques are of increasing interest for operational forestry applications in South Africa, such as estimates of catchment scale evapotranspiration. However, wide-scale adoption of remote sensing techniques may be limited by image costs and data-processing times and costs [49], poor image quality (resulting from cloud cover or smoke), uncertainty regarding the number and timing of images needed to accurately describe annual evapotranspiration, and inappropriate satellite pass-over times. However, a simplified remote sensing regression model proposed by Wang et al. [47] holds promise. In this model, surface net radiation, air or land temperature, and vegetation indices are used to predict evapotranspiration over a wide range of soil moisture contents and land cover types. Wang et al. [47] reported a correlation coefficient of 0.91 between measured and predicted evapotranspiration. Independent validation of the model using measurements on grassland, cropland, and forest collected by the eddy covariance method showed that evapotranspiration could be reasonably predicted with a correlation coefficient that varied from 0.84 to 0.95, a root mean square error that ranged from about 30 to 40 $\mathrm{W\,m^{-2}}$, and a bias that ranged from 3 to 15 $\mathrm{W\,m^{-2}}$. According to Wang et al. [47], the errors encountered could partly be attributed to uncertainty in the eddy covariance method.

3.5. Water Use Efficiency. Water use estimates measured using heat pulse velocity have often been paired with productivity or biomass values to provide water use efficiency

(WUE) estimates. Depending on the objective of a particular study, WUE can be expressed as stem volume production per unit water used, or in the case of bioenergy (see Section 5.2 below), expressed as biomass production (i.e., all components that will be used for bioenergy) per unit water used. Water use efficiency expressed as annual stem volume increment per unit volume of water transpired for *Eucalyptus* species across age classes and site types in South Africa ranges from 0.0008 to 0.0123 m^3 stemwood produced per m^3 water consumed ([5, 26, 28, 40–43]; Table 1).

Water use efficiency varies significantly among *Eucalyptus* clones (for the same age and site) [28]. Evidence of this was presented by Olbrich et al. [5] who found significant clonal differences in WUE between four *E. grandis* clones growing on a high quality site. Clonal WUE, which ranged from 0.0060 to 0.0123 $\mathrm{m}^3\,\mathrm{m}^{-3}$, was related to growth rate, with the most water use efficient clones tending to be the fastest growing [5]. In a lysimeter study, Le Roux et al. [42] investigated variation in WUE among six *Eucalyptus* clones up to the age of 16 months and found significant clonal variation in WUE as well as patterns of growth allocation to roots, stems, branches, and leaves.

Water use efficiency is not a constant characteristic of a given genotype but varies according to the particular combination of site conditions, weather, and tree age [24]. The frequency and duration of soil water deficits is believed to be especially important in governing WUE, which is sensitive to year-to-year variation in rainfall amount as well as rainfall distribution through the year [24]. Dye et al. [28] attributed lower WUE in *Eucalyptus* clones compared to other sample trees to a severe growing-season drought during the period of measurement. Water use efficiency is also influenced by atmospheric humidity (VPD) and changes in carbon partitioning brought about by soil water and nutrient availability [24, 28]. Stomatal closure in response to increasing VPD reduces water loss and generally results in higher WUE, but with a concomitant reduction in photosynthesis and tree growth [39, 50–52].

In nutrient-limited or dry environments, relatively more dry matter is contained in below-ground components (particularly fine roots) of eucalypts than on moist, high-nutrient sites [53–55]. Patterns of carbon allocation can significantly affect WUE, which is higher in trees experiencing better growing conditions, than in those experiencing poorer conditions [28, 56, 57]. Therefore, at the plantation management level, WUE can be maximized by adopting measures which minimize soil water and nutrient deficits [24]. These measures include avoiding removal of forest floor litter, preventing excessive topsoil damage by vehicles, minimizing intense fires which kill herbaceous plants and promote soil erosion, practicing effective weed control, and fertilizing, where economically feasible [24].

Carbon isotopes can also be used to provide estimates of WUE. Isotopic composition of plant carbon ($\delta^{13}\mathrm{C}$) correlates with WUE, where a higher WUE is evidenced by less negative values of $\delta^{13}\mathrm{C}$ [58, 59]. Olbrich et al. [5] presented results showing this relationship for clonal *E. grandis*: the clone with the lowest WUE had more negative $\delta^{13}\mathrm{C}$ values than the

Table 1: Comparative water use efficiency (WUE) values among *Eucalyptus* species and clones grown in South Africa, expressed as annual stem volume increment per unit volume of water transpired (m^3 wood m^{-3} water).

Eucalypt species/clone	WUE (m^3 wood m^{-3} water)	Reference
E. grandis clones	0.0060	[5]
E. grandis clones	0.0123	[5]
E. grandis clones	0.0094	[5]
E. grandis clones	0.0095	[5]
E. grandis	0.0042	[26]
E. grandis	0.0032	[26]
E. grandis	0.0086	[28]
E. grandis	0.0060	[28]
E. grandis	0.0058	[28]
E. grandis	0.0045	[28]
E. grandis	0.0071	[28]
E. grandis	0.0057	[28]
E. grandis	0.0024	[28]
E. grandis	0.0018	[28]
E. grandis	0.0033	[28]
E. grandis	0.0024	[28]
E. grandis	0.0110	[40]
E. grandis	0.0064	[40]
E. grandis	0.0094	[40]
E. grandis	0.0053	[40]
E. grandis	0.0077	[40]
E. grandis	0.0064	[40]
E. grandis	0.0044	[40]
E. grandis	0.0050	[40]
E. grandis	0.0074	[40]
E. grandis	0.0038	[40]
E. grandis	0.0050	[40]
E. grandis	0.0041	[40]
E. grandis	0.0048	[40]
E. grandis	0.0082	[40]
E. grandis	0.0045	[40]
E. grandis	0.0069	[40]
E. grandis	0.0055	[40]
GC15	0.0028	[41]
GC15	0.0048	[41]
GC15	0.0033	[41]
GT529	0.0032	[41]
GT529	0.0049	[41]
GT529	0.0058	[41]
TAG5	0.0045	[41]
TAG5	0.0038	[41]
TAG5	0.0035	[41]
Eucalyptus and hybrid clones	0.0015	[42]
Eucalyptus and hybrid clones	0.0013	[42]
Eucalyptus and hybrid clones	0.0011	[42]

Table 1: Continued.

Eucalypt species/clone	WUE (m^3 wood m^{-3} water)	Reference
Eucalyptus and hybrid clones	0.0008	[42]
Eucalyptus and hybrid clones	0.0010	[42]
Eucalyptus and hybrid clones	0.0014	[42]
Eucalyptus species	0.0034	[43]

other three clones. In a lysimeter study with six *Eucalyptus* clones grown for 16 months under two water regimes (soil water maintained at 100 and 80% of field capacity, resp.), Le Roux et al. [42] reported significant relationships between leaf δ^{13}C values and instantaneous water use efficiencies in the high soil water treatment. However, the lack of relationships between leaf δ^{13}C values and whole-plant, shoot, or stem water use efficiencies in either soil water treatment led these authors to conclude that δ^{13}C may not be a reliable indicator of WUE, but may be useful as a screening tool. Olbrich et al. [5] stated that it is unclear how δ^{13}C varies within eucalypt canopies (e.g., with aspect and branch length) and advised that it may be crucial to follow a rigid sampling procedure. These authors also suggested that canopy microclimate (especially vapor pressure deficit and leaf temperature) may confound relationships between δ^{13}C and WUE.

4. Legislation and Application of Research

Results from the numerous water use studies discussed above have been collated and simplified to provide a scientific basis for South African water use legislation decisions. Since the 1972 law, which dictated that timber growers needed to apply for planting permits to establish new commercial plantations, South African water legislation has undergone a series of refinements, as research results and simulation models have improved [20]. In South Africa's new National Water Act of 1998 (http://www.dwaf.gov.za/Documents/Legislature/nw_act/NWA.pdf, accessed 01.27.2012), all water users are required to register and license and pay for their use of water. Payment for water used by plantation forests is calculated through models developed from the long history of forest hydrological research, using tabulated outputs from paired catchment experiments, process-based studies, and water use estimates using heat pulse velocity and micrometeorological techniques [14].

As of 1999, commercial plantation forestry is classified in the Water Act as a streamflow reduction activity, defined as "... any activity (including the cultivation of any particular crop or other vegetation) ... (that) ... is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly" [60]. The Reserve is the amount of water set aside (i.e., reserved) for environmental flows and to provide for basic human needs such as drinking, food preparation, and hygiene [61]. Under this new water-use licensing system, planning authorities (catchment management agencies) predict the likely hydrological impacts of afforestation and limit the spread of further afforestation in catchments where available water resources are already committed [14, 43]. Ideally, this system should allow sustainable management and equitable distribution of available water resources amongst all water users [16]. As regulation regarding sustainable water resource management needs to be based on results from scientifically defendable work, there is renewed emphasis on the need to understand, accurately model, and manage forest hydrological processes on a national scale [16, 20, 61].

5. Future Considerations

5.1. A New Research Focus. Variable WUE exhibited between different *Eucalyptus* clones should be seen as an opportunity to determine whether it can be exploited to improve the overall production and efficiency of plantation water use [28]. This could be particularly beneficial for forestry situated in marginally dry regions of South Africa where future increases in plantation area are likely to take place given new afforestation constraints under the water law, and as the availability of high-rainfall areas diminishes [5, 24, 28]. In addition, there is also more recent and growing concern over the effects of climate change, especially with regard to decreases in rainfall which are forecast for some forestry areas. Increased efficiency of water use may to some extent offset such detrimental change and provide the industry with a means of adaptation to a changing climate.

The ongoing development of new hybrid *Eucalyptus* clones incorporating diverse genetic potential offers great scope for breeding trees with improved WUE and drought resistance [24, 28]. The challenge, however, will be to tease apart the genetic and environmental influences on WUE for a range of clones and sites [28]. Dye [24] stated that the full potential for improving *Eucalyptus* yields and optimizing WUE will not be achieved without improvements in our understanding of key physiological processes that govern how trees function. Further advances in understanding WUE will stem from process-based models which allow the separate influences of weather, stand characteristics, and site conditions on carbon allocation patterns and transpiration rates to be assessed [28]. These models need to be validated against critical physiological measurements such as sap flow rates, leaf area index, and growth rates to improve our understanding of the linkages between growth and water use [28]. One such model (3-PG) has been verified and can realistically simulate growth and water use in stands of *E. grandis* × *camaldulensis* hybrid clones covering a wide range in age and site growth potential [33].

Given this early stage in our understanding of WUE of plantation trees, and the range of site types in the forestry regions of South Africa, it will be necessary to compare a wide variety of genotypes on uniform sites to obtain comparative WUE data. In particular, the following guidelines are recommended for new research.

(i) Establish trials among a wide variety of clones on uniform high- and low-rainfall sites to compare WUE through direct measurements of growth and sap flow. Because new afforestation is more likely to take place in drier areas which are considered marginal for forestry, growth and WUE on these sites need to be investigated [24]. WUE must be measured over at least a full year to cover seasonal variations in carbon allocation and water use.

(ii) Compare growth and water use among clones that display variation in properties such as stem growth rate, leaf area, angle and density, leaf phenology, and response to drought.

(iii) Perform detailed analyses of canopy structure and physiology to understand differences in patterns of transpiration and photosynthesis. Establish the age at which any differences can be recognized.

(iv) Initiate drought resistance studies that investigate growth, vulnerability to cavitation, water use, and WUE.

(v) Reevaluate the usefulness of carbon isotope ratios for correlations with WUE.

(vi) Estimate below-ground carbon allocation and losses to respiration.

(vii) Use remotely-sensed evapotranspiration techniques for long-term monitoring.

In addition, many breeders have developed plant "ideotypes" to provide conceptual direction for tree selection and improvement programs [62]. The concept of an ideotype in forestry was pioneered by Dickmann [63] as a precise descriptive model of the traits considered desirable for trees in a defined environment. Pereira and Pallardy [62] provided examples of attributes that might be incorporated into a "water-limited biomass production ideotype". These attributes include trees that retain foliage under drought, which would permit continued photosynthesis and growth in environments characterized by substantial, but transient drought periods; degree of genetic control over the pattern of stomatal behavior and thus WUE; and the most effective structure for a root system to provide access to water stored in deep soil horizons [62].

Dye [24] suggested an ideotype for eucalypt clones which includes attributes relating to the following key processes:

(i) canopy structure and efficiency of light interception and transpiration,

(ii) rate of canopy photosynthesis,

(iii) patterns of assimilate allocation,

(iv) root system architecture,

(v) turnover rate of fine roots,

(vi) xylem anatomy and hydraulic architecture,

(vii) drought resistance mechanisms, and

(viii) efficiency of nutrient cycling.

5.2. Growing Eucalypts for Bioenergy Production. There is growing interest in numerous countries for eucalypt plantation-grown bioenergy production. In southern USA for example, *Eucalyptus* has been shown to be a promising biomass for energy production, and commercial plantations are being established at a rate of 5,000 to 10,000 ha per year [64, 65]. According to Dougherty and Wright [65], demand for hardwood from plantation-grown stands for pulp and bioenergy in southern USA is more than 90 million metric tons per year and is increasing. The focus on bioenergy production over the past decade has been largely due to its perceived potential in securing energy supply, reducing greenhouse gas emissions, achieving sustainable development, and improving local economy [66]. However, an increased demand for food in combination with a shift from fossil fuels towards industrial-scale production of energy from lignocellulosic sources will require water, largely from evapotranspiration of biomass production, creating additional demand that must be carefully managed in view of competing users [67–70].

Any type of large-scale changes in land use (e.g., replacing natural grassland with short-rotation eucalypts for bioenergy) could have significant hydrological implications if the water use of the introduced species differs significantly from the vegetation it replaces [61]. The potential impact of land use change therefore depends on the type of native vegetation replaced and on the extent of the land area covered by the new species. In most cases, entire landscapes will not be planted to *Eucalyptus*. For this reason, it will be necessary to determine the proportion of land area occupied by eucalypts before a significant change in streamflow is detected, and how the location of these plantations within catchments (i.e., distance from streams) may relate to streamflow.

Where large-scale changes in vegetation cover are proposed, the differences in evapotranspiration between the current and the proposed vegetation may ultimately translate into changes in available streamflow from that catchment [61]. It is imperative that bioenergy strategies being developed for any country consider water resource impacts together with all other relevant social, economic, and environmental considerations associated with development of this industry [61, 71]. Gush [61] stressed that this is particularly important in countries where there is increasing competition for water, now virtually a global phenomenon.

South Africa, in anticipation of a large demand for land suitable for biofuel production, has developed a national Biofuel Industrial Strategy (BIS) [72]. Under the BIS and new Water Act, it is necessary to assess water use of potential biofuel feedstocks [73]. Water footprint estimates (defined as the amount of water required to produce a unit of energy) have been produced for a range of crops, industries, and countries [67, 69]. However, Jewitt and Kunz [73] stated that whilst these are useful in providing values of the amount of water needed to produce a crop, they are limited for two reasons. Firstly, no consideration is made of a reference or baseline condition so no assessment of impact is possible, and secondly, such "footprints" are typically described at coarse spatial and temporal resolution, whereas water resource impacts are most severely felt at a local level at specific times of the year, for example, low flows prior to the rainy season [18, 73]. Ridoutt and Pfister [74] argued that there is no clear relationship between a water footprint and potential environmental and/or social impact and introduced a revised method which allows comparisons between production systems in terms of their potential to contribute to water scarcity.

King et al. [75] performed a comparative analysis of water use by representative lignocellulosic bioenergy species to provide insight on the best candidate crops for specific climates. In the analysis, the higher biomass productivity group (which included *Eucalyptus* species) had a precipitation : evapotranspiration ratio close to 1.0, compared to the lower productivity group, with a precipitation : evapotranspiration value of about 1.7, indicating that the productive systems were operating at the limit of available water (i.e., using almost all of it). This suggests that future productivity could be vulnerable in regions where water availability is decreased by climate change. In addition, correlations among agroclimatic variables and their relationship to physiological process rates and biomass production suggest that bioenergy productivity will be more sensitive to changes in water availability than temperature under future changes in climate [75]. It is obvious then that water availability will be a key determinant of where and how much biomass-based energy can be produced, as human demand for water grows and climate change increases drought stress in many parts of the world [75].

Based on experience gained in South Africa, Gush [61] provided methodology for assessing the hydrological impacts of tree-based bioenergy feedstocks, from individual tree water use rates to national-scale impacts on water resources. Methodology is needed because large-scale changes in land-use constitute a change in the structure and functioning of vegetation, which has implications for water use and availability of water for downstream users [61]. Gush [61] intended for this to be a generic methodology, not just for South Africa, but with applicability to tree-based bioenergy developments worldwide, and his methods include identifying the geographical area of interest; selecting an appropriate hydrological response unit; identifying "baseline" vegetation in the area of interest; running an appropriate hydrological model to simulate streamflow and evapotranspiration under baseline and future land use scenarios; and drawing conclusions on the likely water resource impacts of the proposed land-use.

6. Conclusions

This review has indicated that extensive information can be drawn from South African studies quantifying the water use of *Eucalyptus* species. Average daily transpiration rates of eucalypts in South Africa range from 2 to 7 mm; these vary with season-associated climatic variables, soil water availability, stand age, and site growth potential. The techniques used to estimate water use, that is, paired catchment experiments, sapflow, modeling estimates, and remote sensing, are widely transferable to other regions.

Results from the long history of forest plantation hydrology have been compiled and are currently used to provide a scientific basis for South African legislation decisions relating to water use estimates and water resource allocation among users. The methodology developed to meet the requirements of South Africa's Water Law has worldwide relevance, as it has the potential to influence future policy and the sustainable management of water in any country faced with water resource management challenges [61]. This type of framework has particular relevance for those countries where proposed land use changes (such as wide scale planting of eucalypts for biomass) may have potential impacts on water resources.

Demand for water, energy, and wood products is steadily increasing, and continued efforts to minimize the impacts of forest plantations on water resources, while conserving productivity gains, are required [24]. A critical component for meeting these increased demands is to improve the efficiency with which afforested areas use available water [5, 43]. In addition, WUE is anticipated to become an important criterion for comparing competing land-use scenarios under the new South African Water Act [24]. Water use efficiency of South African *Eucalyptus* species ranges from 0.0008 to 0.0123 m^3 stemwood produced per m^3 water consumed. These estimates vary with genotype, site conditions, weather, and tree age. Deeper insights into the WUE of eucalypt clones are needed, as certain clones show low water use but fast growth. To further our understanding of WUE, estimates should be paired with physiological measurements and monitoring of stand canopy structure.

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