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Covering letter

Dear Editor,

We wish to re-submit our manuscript with the following details:

Title: Comparison of water-use by alien invasive pine trees growing in riparian and non-riparian zones in the Western Cape Province, South Africa

Authors: Sebinasi Dzikiti [a*], Klaudia Schachtschneider[a], Vivek Naiken[b], Mark Gush [a], David Le Maitre[a]

We are pleased to inform you that we have now thoroughly revised our manuscript and we are grateful for the opportunity you accorded us to revise our paper. The input from the two anonymous reviewers, which has helped us to improve the quality of our manuscript, is also sincerely appreciated.

We hope that our paper will now be accepted for publication in the Forest Ecology and Management Journal.

Sincerely yours,

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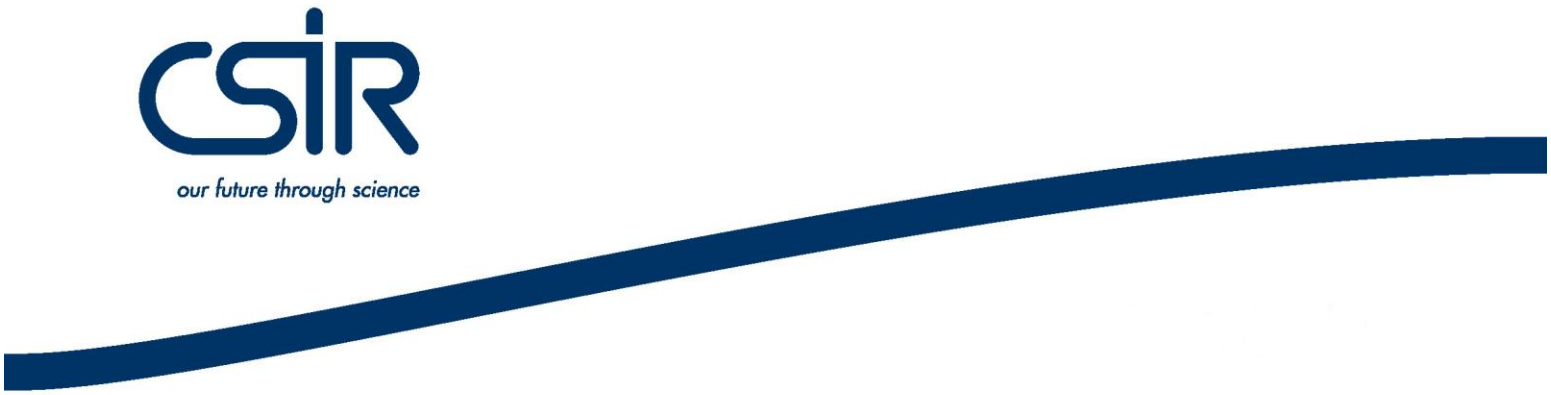
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Comparison of water-use by alien invasive pine trees growing in riparian and non-riparian zones in the Western Cape Province, South Africa

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Abstract

Self-established stands of alien invasive pine trees are common in many parts of South Africa and elsewhere. They mainly invade non-riparian settings but sometimes invade riparian habitats. There are clear visual differences in the physical attributes of trees that occupy riparian and non-riparian zones. We have little information whether the differences between trees growing in these contrasting habitats reflect their water-use. The goal of this study was to establish the water-use of alien invasive pines growing adjacent to and away from a perennial stream, and to determine the driving factors behind the variations. The study was conducted in a self-established 20-year-old mixed pine forest occupied by roughly equal proportions of *Pinus pinaster* and *Pinus halepensis*. Individual tree transpiration rates were measured using the heat pulse velocity (HPV) sap flow method. Evapotranspiration (ET) from entire stands was determined from the surface energy balance equation using sensible heat flux data collected using a boundary layer scintillometer and measurements of the available energy (net radiation – soil heat flux). A simple two-layer model in which the stand ET was calculated as the algebraic sum of the outputs from transpiration (E) and soil evaporation sub-models was evaluated at the two contrasting sites. Annual transpiration and ET rates were higher in the riparian zone at 980 and 1417 mm compared to 753 and 1190 mm, respectively in the non-riparian area. The model predicted stand transpiration fairly accurately for both sites (average R^2 > 0.75), but was less accurate for evapotranspiration (average R^2 < 0.70) due to the difficulties in simulating soil evaporation. No significant differences in sap velocities were found between trees at the two sites so the greater water-use of trees in the riparian zone was due to the larger basal area per stem. Based on the measured transpiration data we conclude that self-sown pine stands growing in riparian zones use at least 36% more water than those occurring in non-riparian settings justifying the high priority given to clearing invasive trees in riparian zones.

Keywords: Sap flow, Scintillometer, Evapotranspiration, Transpiration, Two-source model

1.0 Introduction

Many pine species were introduced into South Africa in the 1800s for the production of timber and other products (Olivier, 2009) and they are still being used for commercial forestry. Currently formal pine plantations cover approximately 660 000 ha of the country (Van Wilgen and Richardson, 2012) and they constitute roughly 87% of the area under forestry in the Western Cape Province. However, some species have propagated beyond the plantation boundaries and have invaded approximately 2.9 million ha of land in South Africa (van Wilgen and Richardson, 2012). At least nine pine species are recognized as being invasive in South Africa and these include: *Pinus elliottii*, *P. halepensis*, *P. patula*, *P. pinaster*, *P. pinea*, *P. radiata*, *P. roxburghii*, *P. taeda* and *P. canariensis* (Rouget et al., 2004).

The impacts of self-established stands of alien plants, such as pines, on the delivery of ecosystem goods and services in South Africa and internationally are well documented (Doody et al., 2011; Hultine and Bush, 2011; Le Maitre et al., 2002; Van Wilgen et al., 2008; Vilà et al., 2011). These include reductions in stream flows (Prinsloo and Scott, 1999), lowering of groundwater levels (Dzikiti et al., 2013; Fourie et al., 2002; Scott et al., 2008), occupying grazing lands (Ndhlovu, 2011; Wise et al., 2012), loss of biodiversity (Dean et al., 2002; Vilà et al., 2011) and exacerbating the problem of wild fires (Van Wilgen and Richardson, 2012). The current rates of spread of invasive pines in catchments in South Africa indicate that many towns, cities and rural areas are likely to experience severe water shortages in the near future (Van Wilgen et al., 2008; Hoffmann et al., 2011).

Alien invasive plants in South Africa result in the loss of ecosystem goods and services, particularly water, which amounts to approximately $800 million per annum at current levels of infestations (De Lange and van Wilgen, 2010). The economic losses will escalate as alien plant invasions continue to spread. Climate change will compound the threat of alien plants on the country's water resources and it is predicted to firstly accelerate the rate of plant spread, with the current invaded area increasing by more than five percent annually (Le Maitre et al., 2000; Richardson and van Wilgen, 2004). More frequent extreme weather events will aid the dispersal of the plants and existing alien plants under the current subtropical conditions will be better suited to the changed climatic conditions. Secondly climate change is predicted to increase the atmospheric evaporative demand in the Western parts of the country (DWA, 2010) thereby increasing the rates of transpiration (Zhu and Ringler, 2012). The outcome of this will be exceptionally high demands on limited water resources thus worsening water shortages in a country where more than 80% of the available water is already allocated (DWA, 2010).

Pines are among the most important invasive taxa in South Africa and are particularly important invaders of the high yielding montane catchment areas (Van Wilgen and Richardson 2012). They mainly invade non-riparian areas and will sometimes invade riparian areas. Clear

visual differences exist between trees growing in riparian and non-riparian zones. Larger trees generally inhabit riparian areas and experiments with plantation trees have shown that plants in riparian areas have the largest impact on surface runoff. For example, Scott (1999) observed that clearing riparian pines led to a 48% increase in surface runoff in a catchment under Mediterranean conditions in the Western Cape compared with between 2.5-10% increases in surface runoff achieved when non-riparian trees were felled. In another study, direct measurements of evapotranspiration by riparian black wattle (*Acacia mearnsii*) plantations in a high rainfall region of South Africa, (Clulow et al., 2011) revealed that the trees used up to 46% more water than the mean annual rainfall and significant reductions in stream flow occurred when the trees achieved full canopy cover. The disproportionate hydrological impacts of riparian trees are a consequence of their access to multiple sources of water for transpiration (Dawson and Ehleringer, 1991). These include recent rainfall, soil water, stream water and groundwater. Trees in non–riparian areas generally have access only to infiltrated rainwater so they are likely to respond differently to changes in water availability than riparian trees.

We have not found any detailed studies which directly investigated the water requirements of self-sown pine forests growing in riparian and non-riparian habitats. This study therefore sought to: 1) quantify the seasonal dynamics of water-use by self-established pine forests growing in riparian and non-riparian settings; 2) identify the key factors influencing the water-use differences in these habitats, and 3) to develop and evaluate a physically-based model of water-use by self-established stands of pines growing in contrasting habitats. This information is crucial not only for understanding the hydrological impacts of alien invasive plants but also for facilitating decision-making, for example, in programs designed to remove alien invasive vegetation in water scarce countries like South Africa.

2.0 Materials and methods

2.1 Study sites

The study sites were situated in a self-established pine forest (S 33.85036° ; E 18.90728°, 510 m asl) on the northern slopes of the Simonsberg Mountain about 18 km north of the town of Stellenbosch in the Western Cape Province of South Africa. The forest is approximately 20 years old, having regenerated after the last wildfire swept through the area in March 1992. Indigenous vegetation in the area is predominantly of the Boland granite fynbos type*, a sclerophyllous* scrub dominated by species of the *Proteaceae*, *Ericaceae* and *Restionaceae* genes, which is typical of the vegetation in the Cape Floral region (Scott, 1999; Mucina and Rutherford, 2006). Remnants of the indigenous vegetation occupied a few open patches in parts of the forest where some clearing had been done recently. The dominant pine species in the forest are *P. pinaster* and the drought tolerant *P. halepensis* and they occur in roughly equal proportions.

Tree density varied widely across the forest from dense almost impenetrable thickets characterized by tall, closely-packed, thin trees in excess of 3500 stems/ha, to less densely invaded areas occupied by larger trees with less than 1100 stems per ha. A perennial stream flows northwards from Simonsberg Mountain through the middle of the riparian study site (Fig 1a) and discharges into the Backsberg farm dam further downstream (north of Fig 1a). At the time of the study the invaded riparian area extended approximately 200 m on either side of the stream and stretched for more than 1.5 km along the length of the stream (Fig 1a). The actual riparian zone (i.e. with seasonally saturated soils) was estimated to be less than 60 m either side of the stream. The non-riparian site was located on an adjacent upland area away from and to the west of the stream, incorporating a small portion (< 2 ha) of a managed pine plantation belonging to the neighbouring Simonsvlei farm (Fig 1b).

The forest floor was covered by a thick layer of pine leaf litter (up to 200 mm deep) in the densely invaded parts of the forest but with relatively shallow litter layers in the less densely invaded sections. The dominant soil type was dark red clayey loam soils with patches of coarse textured sandy loam soils in some places. Climate at the study site was Mediterranean with most of the rain falling during the mild to cold winter season from May to August. Long–term average of yearly maximum and minimum temperatures for the study site are 29 and 6 °C, respectively (van Niekerk and Joubert, 2011) while the long-term average annual rain fall is 812 mm (Schulze and Lynch, 2007).

2.2 Transpiration measurements

Transpiration rates of trees growing at the two sites were determined from sap flow measurements collected over a ten month period from July 2011 to April 2012. Three trees at the riparian and two trees at the non-riparian site were monitored using the heat ratio method (HRM) of the heat pulse velocity (HPV) sap flow measurement technique (Burgess et al., 2001). Four probes were inserted at different depths into the sapwood of each tree at breast height (~1.30 m). Stem diameters of the instrumented trees were selected to be representative of the dominant tree sizes based on measurements on 50 randomly selected trees at each site. At the non-riparian site the diameters at breast height of the instrumented trees were 9.61 cm for Tree 1, and 18.62 cm for Tree 2, respectively. Stem diameters were 11.50 cm for Tree 1, 19.99 cm for Tree 2, and 27.28 cm for Tree 3, respectively at the riparian site. Thermocouple insertion depths from the outer bark were 20, 25, 30, and 35 mm for Tree 1, and 20, 32, 43, and 55 mm for Tree 2 at the non-riparian site. At the riparian site, the thermocouples were installed at 20, 25, 30, and 35 mm for Tree 1, and at 20, 32, 45 and 60 mm for Tree 2, and 20, 40, 60, and 80 mm for Tree 3. More trees could not be instrumented because of equipment limitations. In addition, cable length of the heater probes made sampling trees spaced more than two meters apart difficult

albeit with fewer sensors per tree. Reducing the number of sensors on each tree would have minimized the accuracy of our sap flow measurements because sap velocity varies significantly with radial depth into the sap wood (Wullschleger and King, 2000). Instrumented trees at the riparian site were situated at most 7-8 m away from the stream so they were well within the riparian zone.

The sap flow data was collected at hourly intervals throughout the study period. Occasional equipment malfunctioning, mainly heater failure, led to gaps in the data which were filled in by correlating readings from adjacent probes within the same treatment. The instrumented trees were felled at the end of the study to determine the wound sizes (due to sensor implantation), fractional water content of the wood, wood density and to determine the size of the conducting sapwood areas (Mörling and Valinger., 1999). The sap velocity data was corrected for wounding according to the procedure developed by Swanson and Whitefield (1981). Total sap flow of individual trees was calculated by summing the product of mean sap velocity and the sapwood areas corresponding to the sampled areas. Stand level transpiration (in mm/h) was then determined as the weighted sum of water-use by trees in each stem size category using an average tree density of 2300 stems per hectare for both sites. Sap flow data from Trees 1 and 2 at both sites was assigned to the 1-10 cm and 11-20 cm tree size classes, respectively while Tree 3 sap flow data at the riparian site was assigned to the 21-30 cm stem size class with the weighting functions determined from the stem size surveys.

2.3 Soil water and climate data

Volumetric soil water content was measured hourly in the depth range 0-20 cm from the soil surface using CS616 capacitance probes (Campbell Scientific Inc. Logan UT, USA). Hourly weather data was obtained from a climate station operated by the Agricultural Research Council of South Africa (ARC) at an adjacent farm located about two kilometres away from the experimental site at Merle (S33.8626°, E18.92847° and 381 m asl) while the leaf area index (LAI) was determined at selected intervals during the campaign using the leaf area meter (Model LAI 2000, LI-COR, Inc., Lincoln NE, USA). The reference evapotranspiration (ET_o) was calculated using the modified Penman-Monteith equation according to Allen et al (1998).

2.4 Evapotranspiration measurements

The evapotranspiration rate (ET, in W m^{-2}) by entire stands at the riparian and non-riparian sites was estimated using a surface energy balance approach in which ET was calculated as the residual term in the energy balance equation, namely;

$$ET = R_n - G - H \quad (1)$$

where R_n is the net radiation (W m^{-2}) absorbed by the forest, G is the soil heat flux (W m^{-2}) which represents the energy transferred into and out of the ground, and H is the sensible heat flux (W m^{-2}). The sensible heat flux component was calculated from the changes in the refractive index of the air between a transmitter of monochromatic infrared radiation (at 880 nm) and a receiver along fixed transects using the large aperture boundary layer scintillometer (BLS 900, Scintec, AG, German). The yellow dotted lines in Fig 1(a) and (b) depict the scintillometer beam paths at the two sites. Points A and B represent the locations of the transmitter and receiver and the path lengths were 903 and 860 m for the riparian and non-riparian sites, respectively. The effective scintillometer beam height above the vegetation was calculated using detailed transect elevation and tree height data according to the approach described by Savage et al. (2004). Mean height (h) of the tree canopies at both sites, measured using a Vertex Laser II hypsometer (Haglöf, Sweden) was approximately 14.0 ± 1.0 m. On the other hand the mean scintillometer beam height above the ground was approximately 22 and 25 m at the riparian and non-riparian sites, respectively. The beam heights were therefore significantly larger than the height of the roughness elements at both sites ensuring that free convection scaling requirements were met.

The net radiation absorbed by the forest was measured using a net radiometer (Model: Kipp and Zonen, Delft, The Netherlands) installed above the canopies in the middle of the scintillometer beam transects (grey circles in Fig 1). The net radiometer was mounted on an eight meter lattice mast tower fitted with a further seven and half meter extension pole to ensure that the sensor was at least one and half meters above the canopies on average. The soil heat flux was measured using a cluster of four soil heat flux plates (REBS, Inc. Seattle, WA, USA) installed at a depth of 80 mm at various positions within the forest. Because of equipment limitations, ET from the two sites could not be measured simultaneously. Instead, measurements were taken in rotations during short periods typically eight to ten days at each site during the autumn, winter, spring and summer seasons, respectively.

2.5 Modelling water-use by alien invasive pines

The ET measurements were discontinuous so a model was developed to scale up the water-use data to annual values. In this model the forest was partitioned into two distinct layers namely the upper transpiring layer comprising the tree canopies, and the below canopy layer in which we assumed that evaporation from the forest floor was the main source of water. Transpiration (E, in kg m^{-2} s^{-1}) from the canopies was modelled using a Penman-Monteith equation following Granier and Loustau, (1994), in which

$$E = \frac{sR_n + \rho c_p g_b (e_s(T_a) - e_a)}{\lambda \left[s + \gamma (1 + \frac{g_b}{g_c}) \right]} \quad (2)$$

where λ is the latent heat of vaporization of water (J kg^{-1}), "s" is the slope of the saturation vapour pressure against temperature curve (Pa $°C^{-1}$), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure (J kg^{-1} $°C^{-1}$), $e_s(T_a)$-e_a is the vapour pressure deficit (VPD) of the air (Pa), γ is the psychrometric constant (Pa $°C^{-1}$), g_b and g_c are the aerodynamic and canopy conductance (m s^{-1}), respectively. The aerodynamic conductance (g_b=1/r_b) was calculated using the equation for the leaf boundary layer resistance (r_b, s m^{-1}) adopted from Iritz et al. (1999):

$$r_b = \left(\sqrt[b]{\frac{u_z}{w_c}} \right)^{-1} \qquad (3)$$

where b = 0.01 (m $s^{-0.5}$), u_z is the wind speed (in m s^{-1}) at the effective height (x) where most of the transpiration can be considered to be occurring, w_c is the leaf width which was taken to be 1.0 mm for pine. The wind speed at the effective height was determined following Monteith and Unsworth, (1990) as:

$$u_z = \frac{u^*}{k} \ln\{(x-d)/z_o\} \qquad (4)$$

where u* is the friction velocity, k is the von Karman constant, d is the zero plane displacement and z_o is the roughness length. The zero plane displacement was calculated from mean tree height as d = 0.63h while the roughness length was derived from z_o = 0.13h according to Shuttleworth and Wallace (1985), where h is the mean tree height. For simplicity, the effective height (x) was set at the top of the canopies (14 m). For periods outside the ET measurement campaigns, R_n above the canopies was derived from the hourly solar irradiance data assuming a surface albedo of 0.20 given the dense cover of photosynthesizing plant material. The downward long wave radiation component was calculated from the mean air temperature and actual vapour pressure of the air according to the relationship by Brutsaert (1975) while the long wave radiation emitted by the forest surface at each site was derived using the relationship adopted from Ortega-Farias, (2000) which assumed that the temperature of the effective emitting surface in the forest was equal to the measured air temperature. The simulated net radiation absorbed by the forest agreed well with the measured values (R^2 > 0.85) during different seasons.

Various mathematical formulations exist for the canopy stomatal conductance (g_s) of pine trees (Granier and Loustau, 1994; Poyatos et al., 2007). The data available from this study best suited Granier's formulation/equation:

$$g_s = k_1 . \left(\frac{R_s}{R_s + k_r} \right) \left(\frac{1 - k_{d1}.VPD}{1 + k_{d2}.VPD} \right) \left[1 - k_{s1} \exp(k_{s2}.\delta M) \right] \qquad (5)$$

where k_1, k_{d1}, k_{d2}, k_r, k_{s1}, and k_{s2} are parameters determined by model optimisation, and δM is the soil moisture deficit estimated from:

$$\delta M = \frac{M_{\max} - M}{M_{\max} - M_{\min}} \quad (6)$$

where M_{max}, M_{min}, and M are the maximum, minimum and the actual measured soil water content.

However, the best fit between the measured and modelled transpiration data at both sites was obtained when equation 5 was multiplied by a temperature stress function used on pines by Poyatos et al. (2007) of the form:

$$f(T) = \frac{T_a - T_{\min}}{T_{opt} - T_{\min}} \frac{T_{\max} - T_a}{T_{\max} - T_{opt}} \quad (7)$$

where T_{max} , T_{min} and T_{opt} are the maximum, minimum and optimum temperatures which were set at 40, 0 and 27 °C, respectively and T_a is the measured air temperature. According to Shuttleworth and Wallace (1985), the soil evaporation (E_s, in kg m^{-2} s^{-1}) can be simulated using the relationship;

$$E_s = \frac{\rho c_p}{\gamma \lambda} . \left\{ \frac{e^*(T_s) - e_s}{r_s} \right\} \quad (8)$$

where $e^*(T_s)$ is the saturated vapour pressure at the soil temperature, e_s is the actual vapour pressure of the air but at the soil temperature (T_s) and r_s (in s m^{-1}) is the soil/substrate surface resistance to water vapour transport. The soil temperature was measured during the ET campaigns using the soil averaging thermocouples (Model TCAV-L: Campbell Scientific, Inc., Logan UT, USA). Simple regression equations between soil temperature and air temperature were developed and used to estimate the soil temperature for periods outside the ET measurement campaigns. Poyatos et al. (2007), working in a Scots pine forest using lysimeters, derived a relationship between the soil surface resistance (r_s) and volumetric water content of the substrate at 15 cm depth (θ_{15}) by fitting a power function of the form:

$$r_s = c_1 \left(\frac{\theta_{15}}{\theta_{15\_FC}} \right)^{c_2} \quad (9)$$

where c_1 and c_2 are further parameters to be obtained by model optimization. In this study we set θ_{15} to be equal to the measured volumetric soil water content (M) in equation 6. θ_{15_FC} is the measured volumetric water content at field capacity at 15 cm depth which we considered to be equivalent to the volumetric water content 24 hours after sustained heavy rain events that were

adequate to wet the entire soil profiles and measured in the 0 to 20 cm depth range using the CS616 probes. The estimated volumetric water content at field capacity was approximately 0.22 $m^3 m^{-3}$.

3.0 Results

3.1 Microclimate, soil water and plant attributes

From 1 May 2011 until 30 April 2012, approximately 969 mm of rainfall was received in the study area. The reference evapotranspiration (ET_o) was approximately 1318 mm during the same period. Air temperature peaked at 40.4 °C in summer (mid January 2012) and a minimum of approximately 4.2 °C was reached in late winter (August 2011) (Table 1). Volumetric soil water content in the shallow soil layers (0 to 20 cm depth range) was similar between the two sites during winter (Fig 2) because of the frequent heavy rains which kept the water content above 0.20 m^3/m^3 and small differences were observed for all the other seasons. The similarity in the soil types between the two sites and the presence of a thick leaf litter layer which suppressed direct evaporation from the soil ensured that the soil water regimes did not differ significantly.

Despite the similar soil water regimes there were clear differences in tree physical characteristics based on the random sampling of stem sizes at the two sites. Stem diameters were generally smaller for non-riparian trees, with approximately 66% of the sampled plants having a stem diameter <15 cm and there were no trees with stem sizes >25 cm (Figure 3). In contrast, only 38% of the trees sampled at the riparian site had stem sizes < 15 cm and 16% of the trees had diameters >25 cm. Stem sizes in the range 11 to 15 cm were most common at both sites. The leaf area index (LAI) for the riparian stand was 29% greater than that of the non-riparian stand with values of 2.01 $\pm$ 0.20 and 1.53 $\pm$ 0.20, respectively.

3.2 Transpiration dynamics

During the wet season the measured daily transpiration varied linearly with the atmospheric evaporative demand [depicted by the reference evapotranspiration (ET_o)] for the non-riparian (Fig 4a) and riparian pine trees (Fig 4b). Soil water availability was not limiting because of the winter and early spring rains (Fig 2). The wet season transpiration data extended from early July, when the sap flow measurements commenced to end of September 2011, when both the rainfall frequency and amounts were tapering off (Figs 4a,b). The ratio of the monthly total stand transpiration to the monthly ET_o (K_{cb}) peaked in July at 1.06 and 0.80 for the riparian and non-

riparian sites, respectively (Fig 5). However, a comparison of the measured daily transpiration with the daily ET_o data recorded over all the seasons (entire sap flow measurement period) showed a strongly non-linear relationship for trees in both the non-riparian (Fig 4c) and the riparian (Fig 4d) settings. The ratio of the monthly total transpiration to the monthly ET_o reached its minimum at the end of the dry season in March 2012 with values of 0.56 for the riparian and 0.42 for the non-riparian site.

Despite the presence of alternative water sources for riparian trees during the dry season (e.g. soil water, river water and groundwater), transpiration levels still declined significantly, most likely in response to the soil water depletion given the linear transpiration-ET_o relationship in Fig 4 a & b when soil water was not limiting. The sources of water-used by the trees were not determined in this study and therefore it was not possible to ascertain the level to which the riparian trees depended on, for example, the ground and river water sources. Although transpiration by trees at both sites responded similarly to environmental factors, total transpiration over the whole period when sap flow was monitored (July 2011 to April 2012) was 869.6 mm and 638.3 mm at the riparian and non-riparian sites, respectively. This represented 36% greater transpiration at the riparian than at the non-riparian site.

3.3 Seasonal water-use comparisons

Four measurement campaigns were conducted during the autumn, winter, spring and summer seasons, respectively to measure evapotranspiration (ET) at the study sites (Table 2). The ET model described in section 2.4 was developed in the Model Maker software package (Cherwell Scientific, UK). Model optimization to identify parameters that minimized the weighted sum of squared differences between the measured and modelled transpiration and soil evaporation, respectively was done using the Marquardt iterative method. Combined data from the riparian and non-riparian sites collected during spring (Table 2) was used for optimizing the model (Table 3). No direct measurements of the soil/substrate evaporation were done so the differences between the measured stand level ET and the transpiration were used as proxy for soil/substrate evaporation. Model validation was done using the data collected only during the late summer to early autumn campaign from February to March 2012. Data collected during the other campaigns, notably autumn 2011 and winter 2011, were not used either because they were incomplete (e.g. missing transpiration data in autumn 2011) or unreliable (e.g. the winter scintillometer data) due to poor visibility because of mist or fog at this montane site and condensation inside the scintillometer receiver lens on some occasions.

Simulations of the stand ET were within 19% of the measured values (Fig 6a) at the riparian site while transpiration simulations were relatively more accurate being within 13% of the measured values (Fig 6b). However, model predictions of soil evaporation were poor (Fig 6c) and this

362 contributed towards the larger errors in the predicted ET. At the non-riparian site, the model
363 simulations of both the stand ET and transpiration were within 5% of the measured values (Fig
364 7a,b) despite the poor soil evaporation simulations (Fig 7c). In addition, the scatter in the water-
365 use simulations at the non-riparian site tended to be larger (low R^2) than those at the riparian
366 site.

367 Lastly, the model was then used to determine the monthly transpiration (Fig 8) and
368 evapotranspiration (Fig 9), respectively of the riparian and the non-riparian sites over an entire
369 year. Input data required to run the model included the solar irradiance, wind speed, air
370 temperature, relative humidity, leaf area index and the volumetric soil water content. Total annual
371 transpiration comprising measured data for the period July 2011 to April 2012 and modelled
372 transpiration for the period May-June 2011 was 980 mm for the riparian compared with 753 mm
373 for the non-riparian trees while the modelled annual ET values were 1417 mm for the riparian
374 and 1190 mm for the non-riparian sites.

375

376 **4.0 Discussion**

377 The dynamics of water-use by mature self-established stands of *P. halepensis* and *P. pinaster*
378 growing in riparian and non-riparian environments were determined in this study. Seasonal
379 trends in water-use were similar between the two sites (Fig 4) although riparian trees had much
380 larger stem sizes and used larger quantities of water than those in non-riparian zones.
381 Observations that riparian vegetation is structurally different from non-riparian vegetation and
382 that riparian trees use large quantities of water are consistent with the outcomes of previous
383 studies (Clulow et al., 2011; Dye and Jarmain, 2004; Hultine and Bush, 2011., O'Grady et al.,
384 2002; Scott, 1999). Eco-hydrological investigations by Smith et al (1991) in Sierra Navada (USA)
385 found that riparian trees along river reaches subject to stream diversions had reduced leaf areas,
386 leaf thickness, significantly lower stomatal conductance and midday leaf water potential than
387 similar species along un-diverted reaches. These structural differences likely translated to
388 differences in water-use by the vegetation in the two habitats although no comparative water-use
389 data was collected. Clulow et al. (2011) working with black wattle (*Acacia mearnsii*) plantations
390 observed that riparian trees maintained high growth rates even during the dry season and that
391 the annual total water-use by the plantation exceeded rainfall.

392 In the present study, measured transpiration data showed that riparian pines used up to 36%
393 more water than non-riparian pines while the leaf area index was approximately 29% greater for
394 the riparian trees. It therefore appears that in the case of the self-established pine stands studied
395 here, the greater water-use by riparian trees (compared with those in non-riparian areas) was
396 due to tree physical attributes such as a larger stand basal area (Fig 3) and a larger transpiring
397 leaf area (Verbeeck et al., 2007). However, Hultine and Bush, (2011) observed that there can

also be significant differences in the hydraulic properties of trees growing in riparian and non-riparian settings. Their study revealed that riparian trees tended to have larger xylem vessel diameters and had higher hydraulic conductivities than non-riparian trees. But we did not observe any significant differences in the sap velocities for trees at the two sites in the present study even under high atmospheric evaporative demand and non-limiting soil water conditions.

Most pine species including *P. halepensis* and *P. pinaster* are known to be isohydric, i.e. they close their stomata as soil and atmospheric conditions become dry, thereby maintaining a relatively constant leaf water potential (Klein et al., 2011; Lagergren and Lindroth, 2002). When soil water was readily available at both the riparian and non-riparian sites during the winter rainy season, a linear relationship was observed between the transpiration rates and the reference evapotranspiration (ET_o) (Figs 4a & b). However, a significant departure from linearity occurred as both the atmosphere and soils became drier during the summer and autumn seasons, suggesting a strong tendency by the two pine species to reduce stomatal conductance to prevent potentially harmful declines in tree water status (Figs 4c & d). But the decline in the daily transpiration rates was slower for the riparian trees suggesting that these trees likely maintained a relatively higher stomatal conductance. Lagergren and Lindroth (2002) working on Scots pine (*P. sylvestris*) observed a steep decline in the sap flow rates with increasing vapour pressure deficit (VPD) of the air while (Schiller and Cohen, 1995) observed that the transpiration rates of *P. halepensis* dropped at a rate as much as 0.5 mm d^{-1} (on cloudless days) after the last rains. In our study however, VPD levels exceeding 3.50 kPa were prevalent during the dry summer and autumn months and this possibly contributed to the lowering of the transpiration rates. Mean daily transpiration rates on clear days for the riparian and non-riparian pines peaked at 33 and 26 litres per tree per day, respectively during late winter in August 2011 but dropped to as low as 15 and 11 litres per tree per day in autumn (April 2012) towards the end of the dry season.

However, the substantial decline in the transpiration rates of the riparian pines during the dry season was not expected given that the trees probably had access to multiple sources of water. But Dawson and Ehleringer (1991) demonstrated that not all trees growing close to rivers use river water. Therefore it is possible that the sources of water used by the riparian pines were fewer than we thought and the trees experienced significant water stress. Borghetti et al (1998) observed significant xylem cavitation in *P. halepensis* when subjected to prolonged drought and this could be an additional factor that further reduced the observed transpiration rates at both sites although no data was collected to confirm this in the present study.

Water-use by the riparian and non-riparian pine forests was modelled using a two-source model in which the evapotranspiration (ET) was derived from transpiration and soil evaporation sub-models. Simulations of transpiration were significantly improved by modifying the stress function of the canopy conductance model developed by Granier and Loustau (1994), to include a temperature stress function, and we adopted the version proposed by Poyatos et al. (2007).

Comparison of the hourly transpiration simulations with the measured sap flow data gave accurate predictions at both sites, although less reliable results were obtained for the ET simulations, mainly as a result of the poor model simulations of the soil evaporation. The predicted soil evaporation was much lower than the estimated residual values (ET- minus transpiration) because of the inherent assumptions in our model. The model considered the entire forest to be comprised of only pine trees and the soil and yet there was some understory vegetation mainly in the form of indigenous trees and shrubs whose transpiration was not quantified in this study.

5.0 Conclusions

Comparisons of the dynamics of water-use by alien invasive pine forests in the Western Cape, South Africa reveal that the seasonal water-use trends were similar for trees invading riparian and non-riparian areas although transpiration rates were greater in the riparian zones. Annual transpiration by the riparian pines exceeded rainfall by approximately 8% while transpiration by the non-riparian trees was 83% of annual rainfall. Each hectare of invasive pines directly withdrew about 9.8 million litres of water per year in the riparian zone compared with 7.5 million litres at the non-riparian site. Annual evapotranspiration, on the other hand, was 1417 mm for the riparian and 1190 mm for the non-riparian zone. Independent water use measurements on stands of indigenous Fynbos vegetation at locations within 10 to 15 km from our study site showed annual evapotranspiration rates of 1332 mm in riparian and 757 mm in non-riparian areas with an overall ET range of 600-900 mm (Scott et al. 2000; Dye et al., 2008). Incremental water use per year due to the presence of pine invasions in the Fynbos area consequently translates to approximately 433 mm in the non-riparian and 85 mm in the riparian areas, respectively. Dye et al (2008) attributed the high riparian Fynbos evapotranspiration rates to the high leaf area index and evergreen nature of the riparian plant species which also form dense stands with taller plants than in non-riparian settings. The presence of pine invasions in the Fynbos biomes clearly increases evaporative losses beyond what the baseline vegetation consumes. Targeted efforts to remove the pines from the Fynbos areas in the water scarce Cape region by organizations such as the Working for Water (Department of Environmental Affairs in South Africa) are therefore justified to conserve the unique biodiversity of the region as also confirmed by a recent study by Van Wilgen and Richardson (2012).

This study also demonstrates that the extent to which water-use by riparian invasive species exceeds that by similar species in non-riparian settings depends on the extent to which the riparian vegetation is more structurally developed (e.g. greater leaf or basal area) compared with the non-riparian plants. Based on the logic that in the long-term, stream flow reductions by vegetation is proportional to the difference between precipitation and ET, this study suggests that

the extent of the hydrological impacts depends on the degree to which the invading vegetation is structurally developed. There are other factors which also play a part in stream flow reductions such as the density of the invading vegetation (number of trees per unit area) and these are the subject of our ongoing studies.

The simulations of stand transpiration at each site were reasonable and can be used to estimate direct water-uptake by invasive pine trees. Further improvements are required in the parameterization of the below canopy environment (e.g. by taking into account transpiration by the understory vegetation) and the role of the leaf litter to improve the modelled estimates of evapotranspiration.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. FAO, irrigation and drainage paper 56. Rome.

Borghetti, M., Cinnirella, S., Magnani, F., 1998. Impact of long term drought on xylem embolism and growth in P. halepensis Mill. Trees. 12, 187-195.

Brutsaert, W. H., 1975, On a derivable formula for long-wave radiation from clear skies, Water Resour. Res., 11, 742– 744.

Burgess, S.O., Adams, M., Turner, N., Beverly, C., 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants, Tree Physiol. 21, 589-598.

Clulow, A.D., Everson CS., Gush MB. 2011. The long term impact of *acacia mearnsii* trees on evaporation, streamflow and groundwater resources. WRC report no. TT 505/11. November 2011.

Dawson, T.E., Ehleringer, J.R., 1991. Streamside trees that do not use stream water. Nature. 350, 335-336.

Dean WRJ., Anderson MD., Milton SJ., Anderson TA., 2002. Avian assemblages in native acacia and alien Prosopis drainage line woodland in the Kalahari, South Africa. J. Arid. Environ. 51, 1 - 19.

De Lange, W.J., Van Wilgen, B.W., 2010. Economic assessment of the contribution of biological control to the management of invasive alien plants and to the protection of ecosystem services in South Africa. Biol. Invas. 12 4113-4124.

Doody, T.M., Nagler, P.L., Glenn, E.P., Moore, G.W., Morino, K., Huitine, K.R., Benyon, R.G., 2011. Potential for water salvage by removal of non-native woody vegetation from dryland river systems. Hydrol. Proc. 25, 4117-4131.

DWA, 2010. Groundwater strategy-2010. Department of Water Affairs and Forestry, South Africa.

Dye, P.J., Jarmain, C., 2004. Water use by black wattle (*Acacia mearnsii*): Implications for the links between removal of invading trees and catchment stream flow response. S. Afr. J. Sci. 100, 40-44.

Dye, P.J., Jarmain, C., Le Maitre, D.C., Everson, C.S., Gush, M.B., Clulow, A. 2008. Modelling vegetation water use for general application in different categories of vegetation. Water Research Commission of South Africa Report. 1319/1/08.

Dzikiti, S., Schachtschneider, K., Naiken, V., Gush, M., Moses, G., Le Maitre, D.C.. 2013. Water relations and the effects of clearing invasive *Prosopis* trees on groundwater in an arid environment in the Northern Cape, South Africa. J. Arid. Environ. 90, 103 – 113.

Fourie, F., Mbatha, K., Verster, H., van Dyk, G., 2002. The effect of vegetation (*Prosopis* Sp) on groundwater levels in Rugseer river, Kenhardt, South Africa. Department of Water Affairs, South Africa.

Granier, A., Loustau, D., 1994. Measuring and modelling the transpiration of a maritime pine canopy from sap flow data. Agric. For. Meteorol. 71, 61-81.

Hoffmann, J.H., Moran, V.C., van Wilgen, B.W., 2011. Prospects for the biological control of invasive pinus species (Pinaceae) in South Africa. Afr. Entomol. 19, 393-401.

Hultine, K.R., Bush, S.E., 2011. Ecohydrological consequences of non-native riparian vegetation in the southwestern United States: A review from an ecophysiological perspective. Wat. Res. Resear. 47, 1-13.

Iritz, Z., Lindroth, A., Heikinheimo, M., Grelle, A., Kellner, E., 1999. Test of a modified Shuttleworth-Wallace estimate of boreal forest evaporation. Agric. For. Meteorol. 98, 605-619.

Jones, H.G., 1992. Plants and microclimate: a quantitative approach to environmental plant physiology. Second edition. Cambirdge University Press.

534 Klein, T., Cohen, S., Yakir, D., 2011. Hydraulic adjustments underlying drought resistance of
535 Pinus halepensis. Tree Physiol. 31, 637-648.

536 Lagergren, F., Lindroh, A., 2002. Transpiration response to soil moisture in pine and spruce trees
537 in Sweden. Agric. For. Meteorol. 112, 67-85.

538 Le Maitre, D.C., van Wilgen, B.W., Belderblom, C.M., Chapman, R.A., Nel, J.A. 2002. Invasive
539 alien plants and water resources in South Africa: case studies of the costs and benefits of
540 management. For. Ecol. Man. 160, 143-159.

541 Le Maitre, D.C., Versfeld, D.B., Chapman, R.A., 2000. The impact of invading alien plants on
542 surface water resources in South Africa: A preliminary assessment. WaterSA. 26, 397-408.

543 Monteith, J.L., Unsworth, M., 1990. Principles of environmental physics. Second edition.
544 Butterworth Heinemann.

545 Mörling, T., Valinger, E., 1999. Effects of fertilization and thinning on heartwood area, sapwood
546 area and growth of Scots pine. Scand. J. For. Res. 14, 462-469.

547 Mucina, L., Rutherford, M.C., 2006. The vegetation of South Africa, Lesotho and Swaziland.
548 Strelitzia 19. South African National Biodiversity Institute, Pretoria.

549 Ndhlovu, T., 2011. Impact of Prosopis (mesquite) invasion and clearing on ecosystem structure,
550 function and agricultural productivity in semi-arid Nama Karoo rangeland, South Africa. MSc
551 Stellenbosch University.

552 O'Grady, A., Eamus, D., Cook, P.G., Lamontagne, S., 2002. Comparative water use by riparian
553 trees Melaleuca argentea and Corymbia bella in the wet-dry tropics of northern Australia. 26,
554 219 -228.

555 Olivier, W., 2009. There is honey in the forest: The history of forestry in South Africa.
556 TheSouthern African Institute of Forestry, Pretoria, South Africa.

557 Ortega-Farias, S., Antonioletti, R., Olioso, A., 2000. Net radiation model evaluation at an hourly
558 time step for mediterranean conditions. Agronomie 20, 157-164

559 Poyatos R., Villagarcia L., Domingo F., Piñol J., Llorens P. 2007. Modelling evapotranspiration in
560 a Scots pine stand under Mediterranean mountain climate using the GLUE methodology. Agric.
561 For. Meteorol. 146, 13-28.

562 Prinsloo, F.W., Scott, D.F., 1999. Stream flow responses to the clearing of alien invasive trees
563 from riparian zones at three sites in the Western Cape Province. S. Afr. For. J. 185, 1-7.

564 Richardson, D.M., van Wilgen, B.W., 2004. Invasive alien plants in South Africa: how well do we
565 understand the ecological impacts? S. Afr. J. Sci. 100, 45-52.

566 Rouget, M., Richardson, D.M., Milton, S.J., Polakow, D., 2004. Predicting invasion dynamics of
567 four alien Pinus species in a highly fragmented semi-arid shrubland in South Africa. Plant Ecol.
568 152, 79-92.

569 Savage, M.J., Everson, C.S., Odhiambo, G.O., Mengistu, M.G., Jarmain, C., 2004. Theory and
570 Practice of Evapotranspiration Measurement, with Special Focus on Surface Layer
571 scintillometer (SLS) as an Operational Tool for the Estimation of Spatially-Averaged
572 Evaporation. Water Research Commission Report No. 1335/1/04, Water Research
573 Commission, Pretoria, South Africa.

574 Schiller, G., Cohen, Y., 1995. Water regime of a pine forest under a Mediterranean climate.
575 Agric. For. Meteorol. 74, 181-193.

576 Schulze, R.E., Lynch, S.D., 2007. Annual Precipitation. *In:* Schulze, R.E. (Ed). 2007. *South*
577 *African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA,
578 WRC Report 1489/1/06, Section 6.2.

579 Scott, D.F., 1999. Managing riparian zone vegetation to sustain streamflow: results of paired
580 catchment experiments in South Africa. Can. J. For. Resear. 29, 1149 – 1157.

581 Scott D.F., Prinsloo F.W., Moses G., Mehlomakulu M. and Simmers A.D.A. 2000. A Re-analysis
582 of the South African Catchment Afforestation Experimental Data. Water Research Commission,
583 Pretoria, RSA. Report 810/1/00.

584 Scott, R.L., Cable, W.L., Huxman, T.E., Nagler, P.L., Hernandez, P.M., Goodrich, D.C., 2008.
585 Multilayer riparian evapotranspiration and groundwater use for a semi-arid watershed. J. Arid
586 Environ. 72, 2111-2120.

587 Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops-an energy combination
588 theory. Quart. J. Roy. Meteorol. Soc. 111, 839-855.

589 Smith, S.D., Wellington, A.B., Nachlinger, J.L., Fox, C.A. 1991. Functional responses of riparian
590 vegetation to stream flow diversion in the eastern Sierra Navada. Ecol. Appl. 1, 89-97.

591 Swanson, R.H., Whitfield, D.W.A., 1981. A numerical analysis of heat pulse velocity theory and
592 practice. J. Exp. Bot. 32, 221-239.

593 Van Niekerk, A., Joubert, S.J., 2011. Input variable selection for interpolating high-resolution
594 climate surfaces for the Western Cape. WaterSA. 37, 271 – 279.

595 Van Wilgen, B.W., Richardson, D.M., 2012. Three centuries of managing introduced conifers in
596 South Africa: benefits, impacts, changing perceptions and conflict resolution. J. Environ. Man.
597 106, 56-68.

598 Van Wilgen, B.W., Reyers, B., Le Maitre, D.C., Richardson, D.M. & Schonegevel, L. 2008. A
599 biome-scale assessment of the impact of invasive alien plants on ecosystem services in South
600 Africa. J. Environ. Manage. 89, 336-349.

601 Verbeeck, H., Steppe, K., Nadezhdina, N., Op de Beeck, M., Deckmyn, G., Meiresonne, L.,
602 Lemeur, R., Cermák, J., Ceulemans, R., Janssens, I.A., 2007. Stored water use and
603 transpiration in Scots pine: a modeling analysis with ANAFORE. Tree Physiol. 27, 1671-1685.

604 Vilá, M., Espinar, J.L., Hejda, M., Hulme, P.E., Jarosik, V., Maron, J.L., Pergl, J., Schaffer, U.,
605 Sun, Y., Pysek, P., 2011. Ecological impacts of invasive alien plants: a meta-analysis of their
606 effects on species, communities and ecosystems. Ecol. Letters. 14, 702-708.

607 Wise, R.M., van Wilgen, B.W., Le Maitre, D.C. 2012. Costs, benefits and management options
608 for an invasive alien tree species: The case of mesquite in the Northern Cape, South Africa. J.
609 Arid Environ. 84, 80-90.

610 Wullschleger, S.D., King, A.W. 2000. Radial variation in sap velocity as a function of stem
611 diameter and sapwood thickness in yellow-poplar trees. Tree Physiol. 20, 511–518.

612 Zhu T, Ringler C. 2012. Climate change impacts on water availability and use in the Limpopo
613 river basin. Water 4, 63-84.

614

615

616 **Captions**

617 Fig 1. Pine invaded study sites where a) represents the riparian site with a small perennial
618 stream flowing towards the Backsberg farm dam on the northern edge of the image, and
619 b) depicts the non-riparian site. The yellow lines indicate the location of the scintillometer
620 transects and the grey circles the positions of the energy balance systems.

621 Fig 2. Soil water dynamics from 0 to 20 cm depth at the riparian and non-riparian pine sites.

622 Fig 3. Stem size distributions determined from measurements of the stem diameters at breast
623 height of 50 randomly selected trees at the pine invaded sites.

624 Fig 4. Transpiration dynamics of the invasive pine trees in response to the atmospheric
625 evaporative demand during the wet season: (a) at the non-riparian site, and (b) at the

626 riparian site: (c) and (d) transpiration over the whole measurement period. Each data
627 point represents the daily total transpiration at each site.

628 Fig 5. Monthly changes in the ratio between the transpiration rate and ET_o (Kcb) at the pine
629 invaded sites.

630 Fig 6. Validation of the two-source water-use model at the riparian site where (a) shows model
631 predictions for ET, (b) prediction of the transpiration and (c) predictions of the
632 soil/substrate evaporation. The dashed line represents the 1:1 line.

633 Fig 7. Validation of the two-source water-use model at the non-riparian site where (a) shows
634 model predictions for ET, (b) prediction of the transpiration and (c) predictions of the
635 soil/substrate evaporation. The dashed line represents the 1:1 line.

636 Fig 8. Simulated monthly transpiration rates for the riparian and non-riparian invaded sites over
637 an annual time scale.

638 Fig 9. Simulated monthly evapotranspiration rates for the riparian and non-riparian invaded sites
639 over an annual time scale.

640

Highlights

- Self-sown pine trees invading riparian zones used 36% more water than trees in non-riparian areas;
- Greater water-use by riparian pines was a result of larger tree sizes than higher sap flux densities;
- Trees in both habitats closed their stomata under high atmospheric evaporative demand;
- Stand transpiration was accurately predicted by a Penman-Monteith type model in both habitats.

Tables

Table 1. Summary of the monthly air temperature, rainfall and reference evaporation (ET_0) at the study site during this study.

Year	Month	T_{max} (°C)	T_{min} (°C)	Rain fall (mm)	ET_o (mm)
	May	28.9	6.9	142.8	48.5
	Jun	25.9	5.7	178.8	35.9
	Jul	24.8	5.1	58.0	54.5
2011	Aug	25.4	4.2	133.8	59.6
	Sept	31.6	5.3	97.8	79.7
	Oct.	33.3	6.3	42.0	107.9
	Nov	34.5	6.3	89.4	133.2
	Dec	34.2	8.4	47.6	164.4
	Jan	40.4	10.6	11.0	180.8
2012	Feb	39.4	11.8	16.6	185.8
	Mar	37.0	10.5	45.6	169.6
	Apr	33.4	7.0	106	98.9
Average/Total		**32.4**	**7.3**	**969.4**	**1318.8**

Table 2. Total evaporation measurement periods.

Season	Site		
	Riparian	Non-riparian	Application
Autumn	14 - 22 Mar 2011	23 - 31 Mar 2011	Unused
Winter	17 - 24 Jun 2011	25 Jun - 1 Jul 2011	Unused
Spring	26 Oct - 7 Nov 2011	10 - 22 Nov 2011	Calibration
Summer	14 - 24 Feb 2012	25 Feb - 8 Mar 2012	Validation

Table 3. Parameter values for the pine water-use model

Parameter	Value	Units
c_1	0.058	s m^{-1}
c_2	-0.312	-
k_1	0.035	m s^{-1}
k_{d1}	0.00014	Pa^{-1}
k_{d2}	0.00019	Pa^{-1}
k_r	207.53	W m^{-2}
k_{s1}	0.036	-
k_{s2}	0.00015	-

Figures

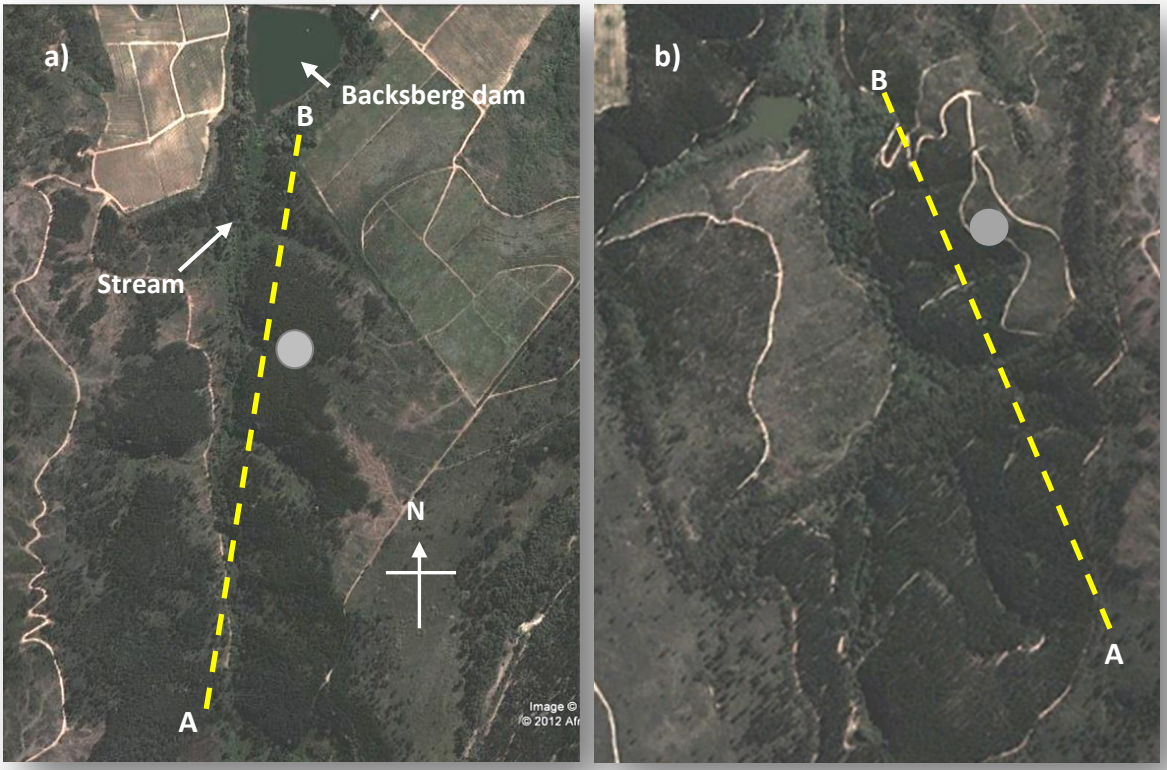

Fig 1.

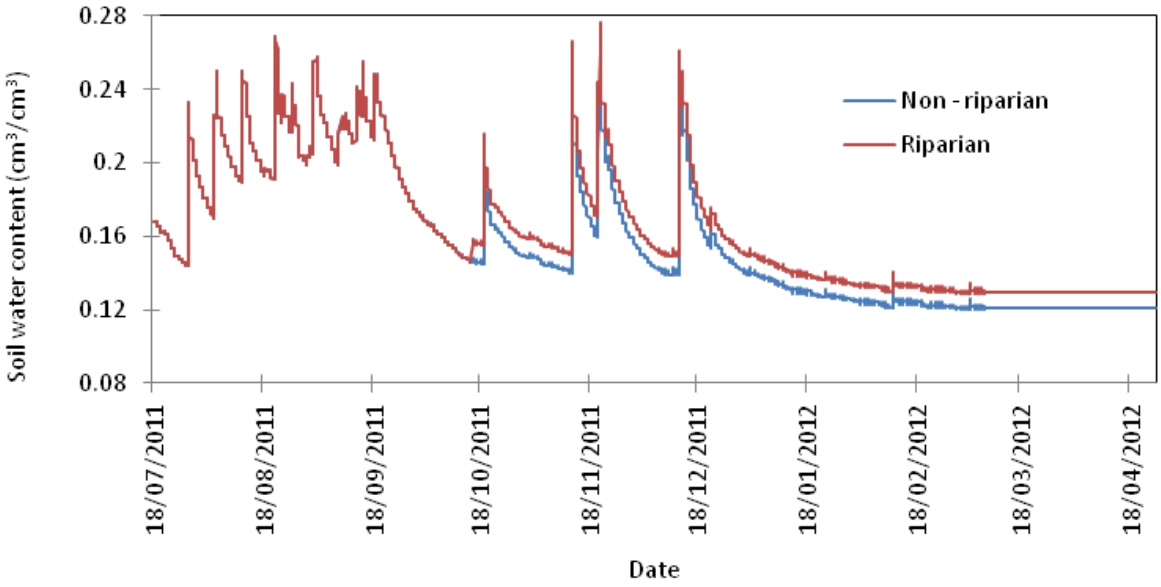
0.28
0.24
0.2
0.16
0.12
0.08
Soil water content (cm³/cm³)
Non - riparian
Riparian
18/07/2011
18/08/2011
18/09/2011
18/10/2011
18/11/2011
18/12/2011
18/01/2012
18/02/2012
18/03/2012
18/04/2012
Date

Fig 2

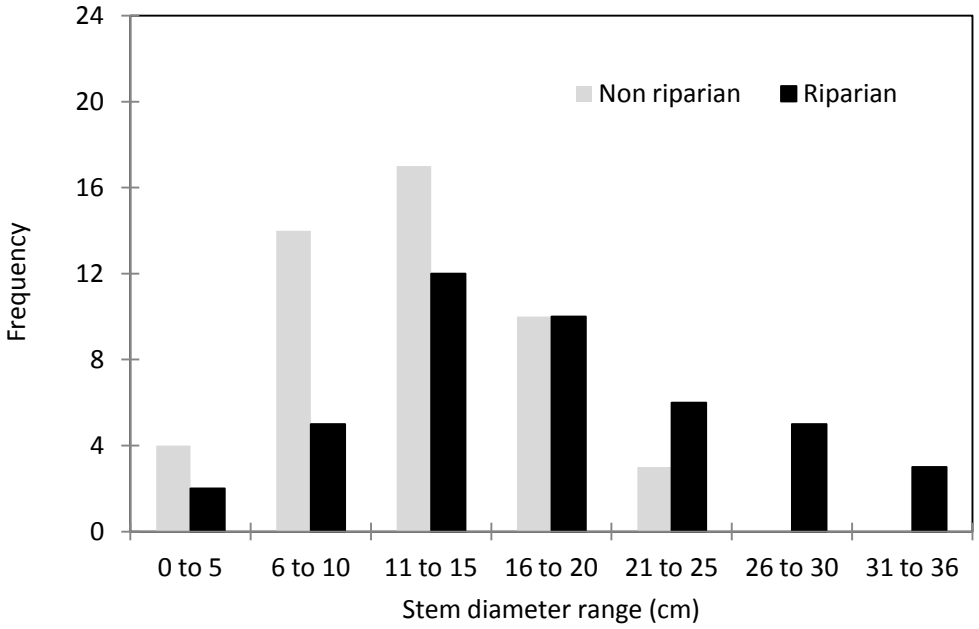
24
20
16
12
8
4
0
Frequency
Non riparian
Riparian
0 to 5
6 to 10
11 to 15
16 to 20
21 to 25
26 to 30
31 to 36
Stem diameter range (cm)

Fig 3.

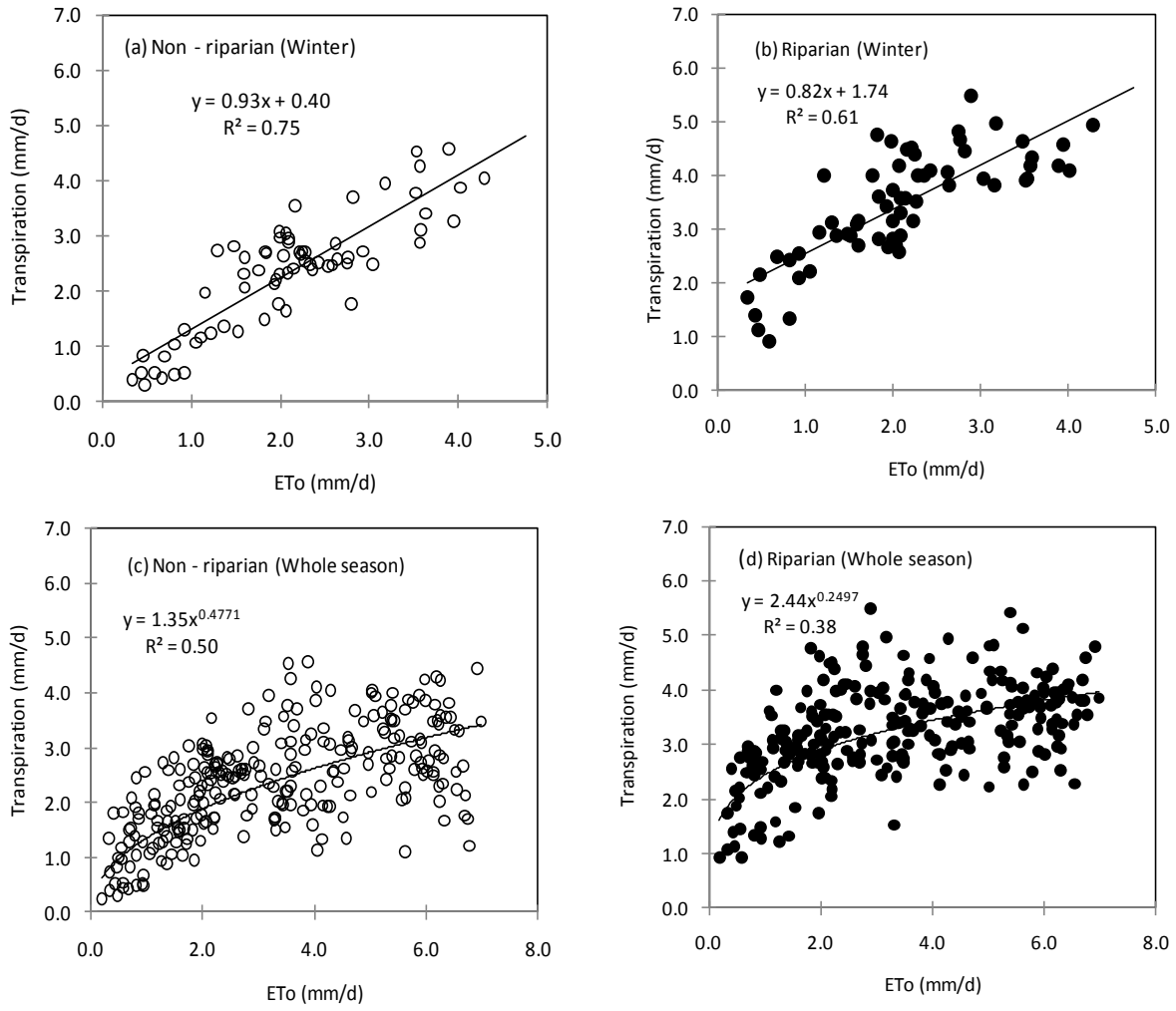
(a) Non - riparian (Winter)
y = 0.93x + 0.40
R² = 0.75
Transpiration (mm/d)
ETo (mm/d)
(b) Riparian (Winter)
y = 0.82x + 1.74
R² = 0.61
Transpiration (mm/d)
ETo (mm/d)
(c) Non - riparian (Whole season)
y = 1.35x^0.4771
R² = 0.50
Transpiration (mm/d)
ETo (mm/d)
(d) Riparian (Whole season)
y = 2.44x^0.2497
R² = 0.38
Transpiration (mm/d)
ETo (mm/d)

Fig 4

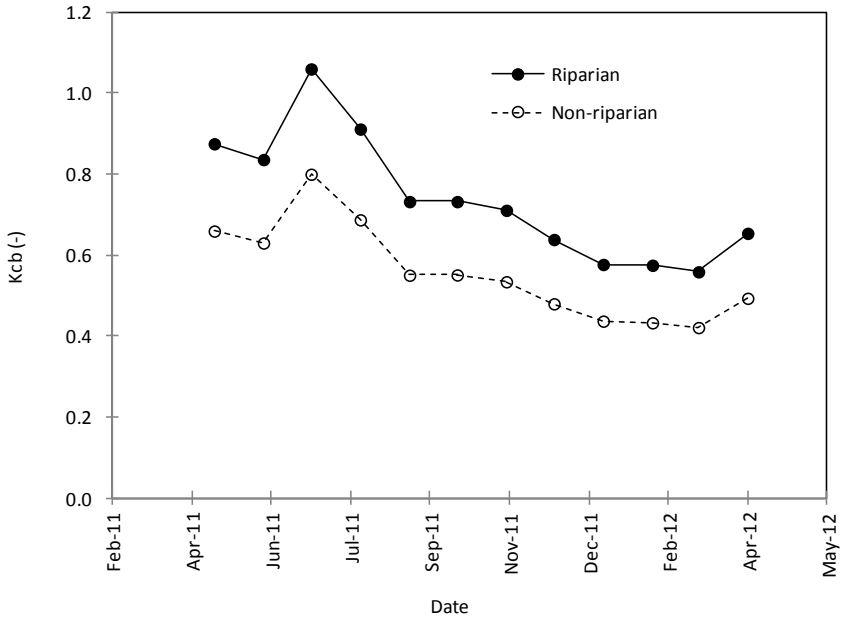
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Kcb (-)
Riparian
Non-riparian
Feb-11
Apr-11
Jun-11
Jul-11
Sep-11
Nov-11
Dec-11
Feb-12
Apr-12
May-12
Date

Fig 5

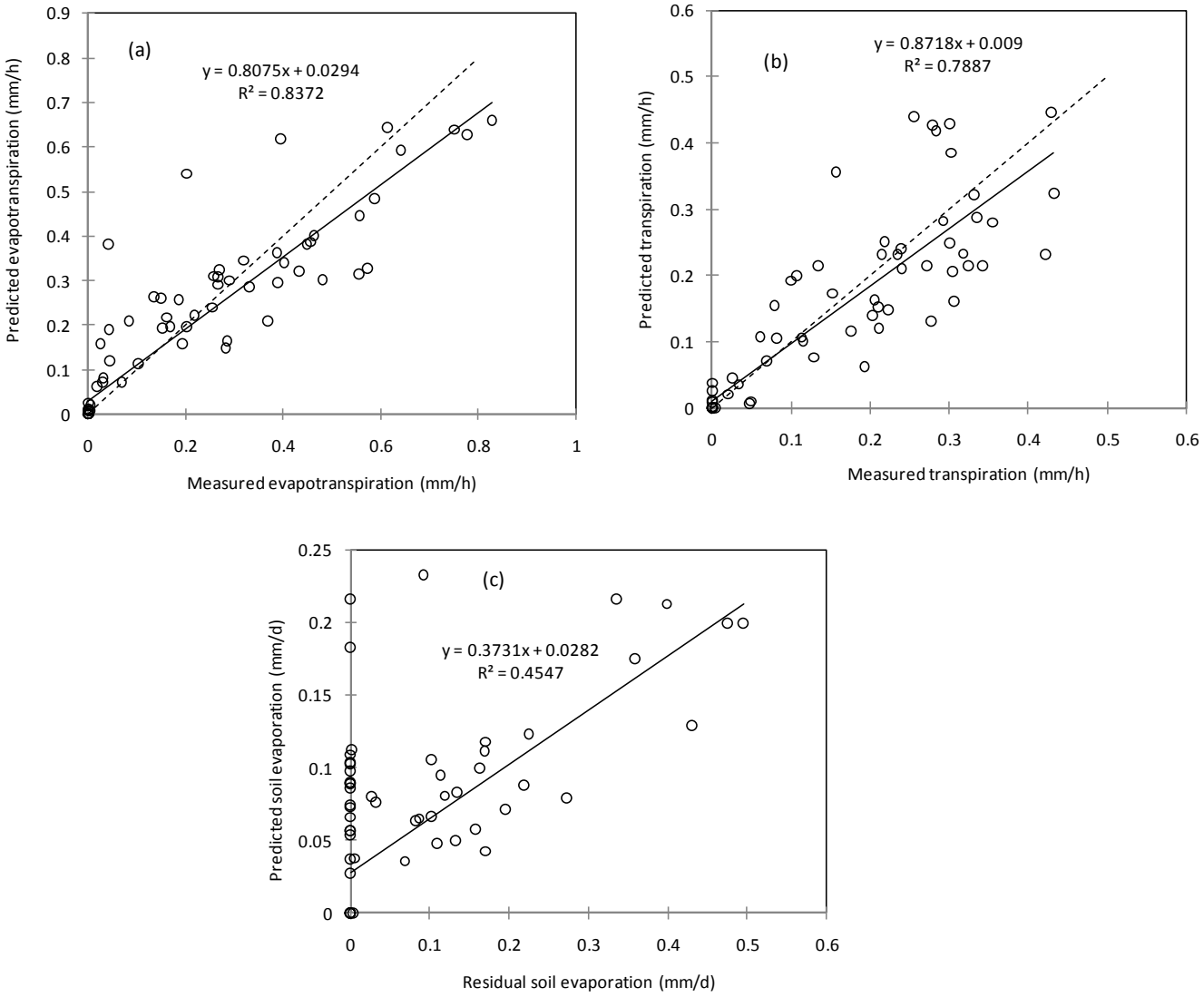
(a)
y = 0.8075x + 0.0294
R² = 0.8372
Predicted evapotranspiration (mm/h)
Measured evapotranspiration (mm/h)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
(b)
y = 0.8718x + 0.009
R² = 0.7887
Predicted transpiration (mm/h)
Measured transpiration (mm/h)
0
0.1
0.2
0.3
0.4
0.5
0.6
(c)
y = 0.3731x + 0.0282
R² = 0.4547
Predicted soil evaporation (mm/d)
Residual soil evaporation (mm/d)
0
0.05
0.1
0.15
0.2
0.25

Fig 6

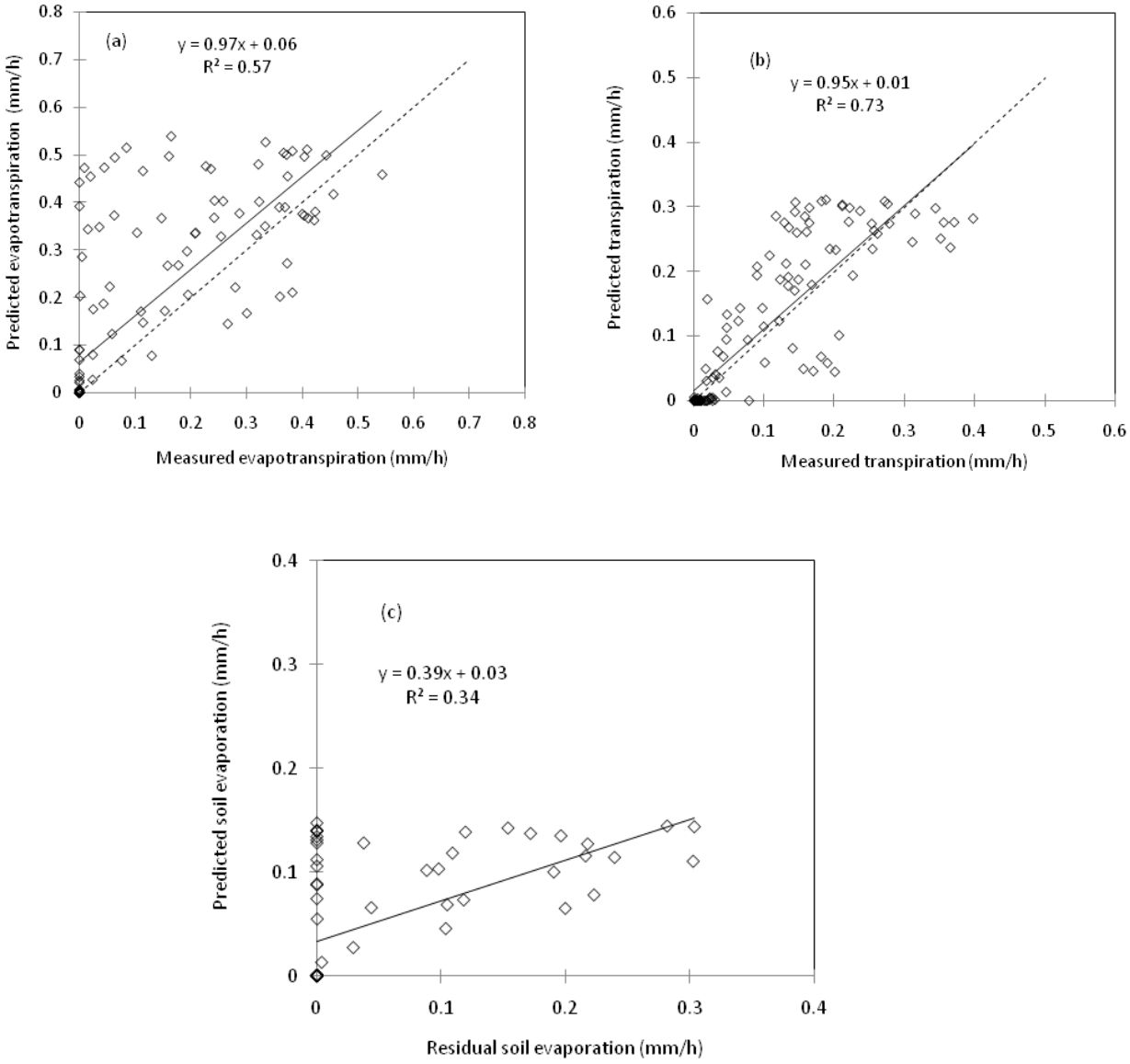
(a)
y = 0.97x + 0.06
R² = 0.57
Predicted evapotranspiration (mm/h)
Measured evapotranspiration (mm/h)
(b)
y = 0.95x + 0.01
R² = 0.73
Predicted transpiration (mm/h)
Measured transpiration (mm/h)
(c)
y = 0.39x + 0.03
R² = 0.34
Predicted soil evaporation (mm/h)
Residual soil evaporation (mm/h)

Fig 7

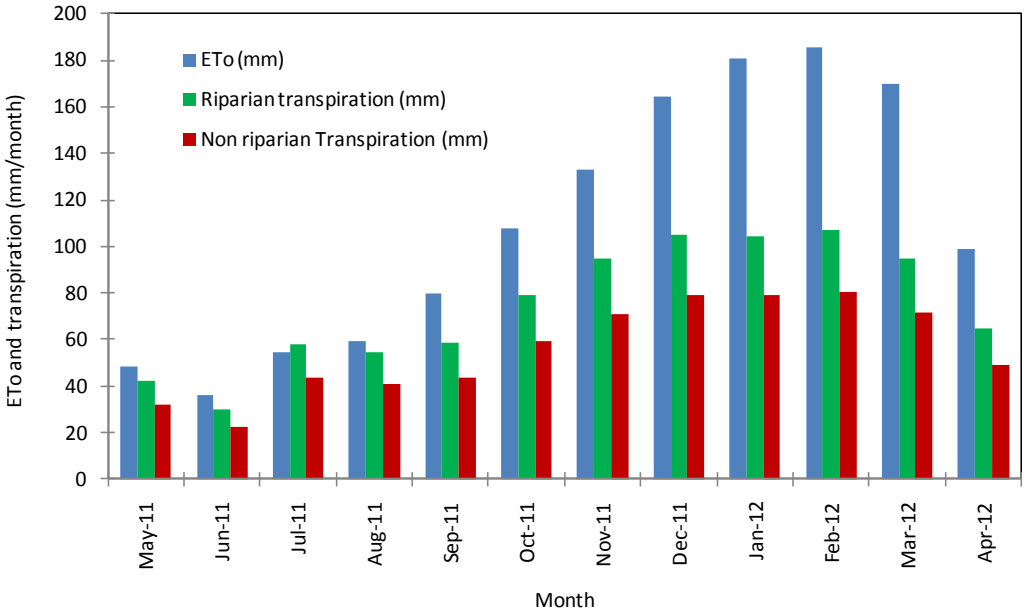
ETo (mm)
Riparian transpiration (mm)
Non riparian Transpiration (mm)
ETo and transpiration (mm/month)
0
20
40
60
80
100
120
140
160
180
200
May-11
Jun-11
Jul-11
Aug-11
Sep-11
Oct-11
Nov-11
Dec-11
Jan-12
Feb-12
Mar-12
Apr-12
Month

Fig 8

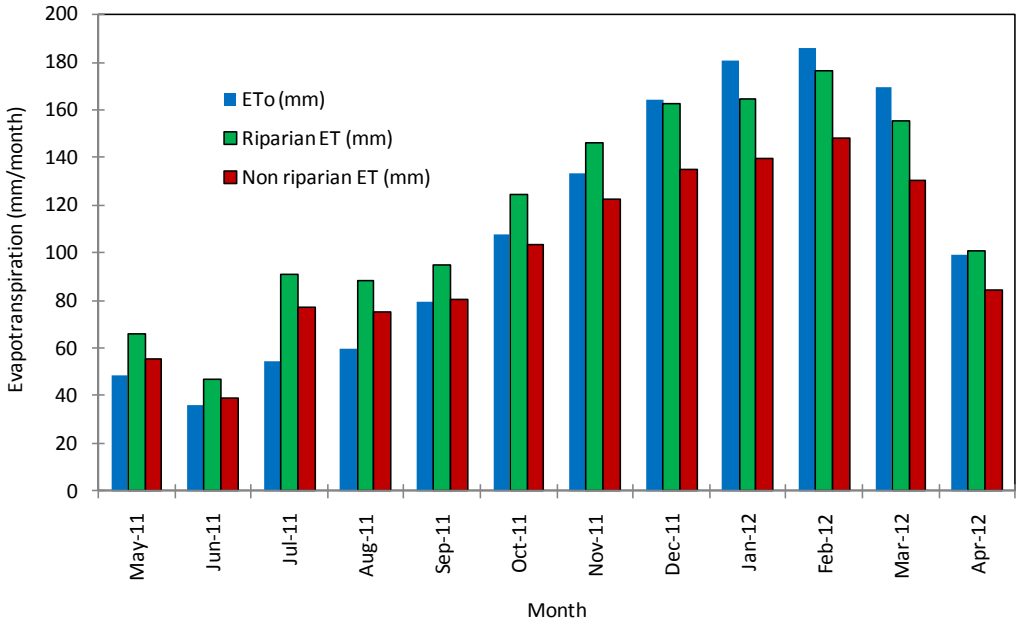
ETo (mm)
Riparian ET (mm)
Non riparian ET (mm)
Evapotranspiration (mm/month)
0
20
40
60
80
100
120
140
160
180
200
May-11
Jun-11
Jul-11
Aug-11
Sep-11
Oct-11
Nov-11
Dec-11
Jan-12
Feb-12
Mar-12
Apr-12
Month

Fig 9

*Reply to reviewers

Dear Editor,

We wish to re-submit our manuscript with the following details:

Title: Comparison of water-use by alien invasive pine trees growing in riparian and non-riparian zones in the Western Cape Province, South Africa

Authors: Sebinasi Dzikiti [a*], Klaudia Schachtschneider[a], Vivek Naiken[b], Mark Gush [a], David Le Maitre[a]

We are pleased to inform you that we have now thoroughly revised our manuscript and we are grateful for the opportunity you accorded us to revise our paper. The input from the two anonymous reviewers, which has helped us to improve the quality of our manuscript, is also sincerely appreciated.

Three main issues were raised by the reviewers and these include: 1) concerns over our sap flow measurement approach, 2) the need to include indigenous baseline vegetation in the assessment of the hydrological impacts of the alien invasive pines, and 3) the management implications of our results, among others.

Regarding the sap flow measurements, we were constrained by inadequate equipment and we agree with the reviewers that it would have been ideal that we sample more trees. However, we had to make a choice between spreading the existing few sensors on more trees so that we would end up with, say one or two probes per tree but ultimately sample more trees than we did. However, we felt that this approach would introduce much larger errors in our sap flow data as it is well known that the sap velocity changes significantly with depth into the sap wood. To obtain representative sap flow data, we therefore decided to sample the sap velocity at four depths within the sap wood of a few trees typical of the dominant size classes at each site. We therefore believe that our tree scale sap flow data is quite accurate and we have clarified our approach in the revised manuscript on page 5 lines 157 to 169 and page 6 lines 168 to 170.

We have now a discussion on the water use by indigenous vegetation, page 14 lines 451 – 460 and the management implications (page 14, lines 460 – 465).

Responses to all the questions raised by the reviewers are detailed below. We repeat the question/ comment raised by each reviewer in italic text and our responses are in non-italics text. The changes made to the manuscript are highlighted in yellow shade.

REVIEWER #1

Comment # 1:
This manuscript was interesting to read and deals with a very important matter that is appropriate for FEM. How invasive species can endanger the water supply in a region. Most of the manuscript read well but some parts of the M&M need to be clarified.

- We are pleased that you found our manuscript interesting and relevant to the FEM journal and we hope we have addressed your concerns satisfactorily.

Comment # 2:
The main shortage of this study is that it is not enough to compare riparian and non-riparian transpiration for "understanding the hydrological impacts of alien invasive plants" (line 109), as you then have to use the indigenous vegetation as reference.

- We agree with this comment and we have extensively revised our manuscript to include the role of indigenous vegetation based on past studies in the Fynbos biome (see page 14 lines 451 to 465.

Comment # 3:
The other major problem is that the data is a little bit weak. There is only 2 respective 3 trees measured for each vegetation type and there is a big question mark behind the stand inventory data needed and the method used to scale up the sap flow data to stand level.

- We have addressed the question of the numbers of the trees sampled in the introduction above, but briefly we decided to collect detailed sap flow data on a few representative trees than on a many trees but with questionable data.
- On the second point regarding the tree inventory, we admit that we unintentionally made a major omission in our original submission in that we did not mention that we did a stem size survey on 50 randomly selected trees per site (100 trees for the two sites). We have now clarified our tree inventory approach on page 5 line 159.

Comment #4:
Line 39. I think you mean evapotranspiration here. Use E as abrevation for transpiration and ET for evapotranspiration throughout.

- Yes, we indeed meant evapotranspiration. Please note that we have replaced the phrase "total evaporation" with the word "evapotranspiration" throughout the manuscript for consistency.

Comment #5:
Lines 82-83. I don't understand the unit of spread, do you mean that the area of invasive species increase with 5% each year?

- We have revised this sentence as suggested (page 3 lines 84 – 85).

Comment #6:
Lines 119. Is "Boland granite fynbos" Latin? Check if it really is common practice to have it in italic font.

- Again we have revised this accordingly (see page 4 line 126).

Comment #7:
Lines 118-121. Hard sentence to read, I suggest "Indigenous vegetation in the area is predominately of the Boland granite fynbos type, a sclerrophyllous scrub vegetation, dominated by species of the Proteaceae, Ericeae and Restinaceae genes, which is typical of the vegetation in the Cape Floral region".

- We have revised the sentence as suggested (page 4 line 126 to 128)

Comment #8:
Lines 136. "up to 200 mm deep" might read better.

- This has been revised accordingly (page 5 line 143).

Comment #9:
Lines 140-141. It is not totally clear what type of average temperatures these are, long term average of yearly maximum and minimum of 24 h mean temperatures?

- we have clarified the type of average temperatures on page 5 line 148.

Comment #10:
Line 150. Is it possible to give some more details about the depths? Also, you don't really tell how you scale of your sap velocities to tree level sap flow.

- We have revised this section extensively also in line with some the earlier comments – see page 5 lines 159 to 167 and page 6 lines 168 to 170.

Comment#11:
Lines 162-164. You have a very limited number of trees. I think you have to tell which size categories you used.

- We have provided more information on size categories used (page 6 line 183 to 186) and the question on the number of trees has been dealt with earlier.

Comment # 12:
Lines 164-165. This seems to be a very weak spot of the study as it sound like you take the number of stems right out of the air. The numbers are exactly the same for both study sites and the scaling up to stand level transpiration if very dependent on this number.

- As explained earlier, we unintentionally did not mention that our tree statistics were based on measurements of the stem sizes of 50 randomly selected trees. However, we had included this information in the caption of Fig 3 but not in the text and we agree that this could cause some confusion. We have now rectified this mistake (pg 5 line 159).
- Regarding the number of trees per site, an average figure for the whole invaded area rather than the specific numbers per site, was more appropriate because the number of trees varies as a complex function of many variables such as soil types, anthropogenic factors, microclimates etc. But we were more interested in understanding how differences in the physiology of the trees at the two sites translated to differences in the quantity of water used.

Comment # 13:
Line 166. A new header for this section would be good.

- We have introduced a new header – page 6 line 188.

Comment #14:
Lines 186-188. Can you give some more details? Height, for instance, seems to be very important according to the manual "The free convection scaling requires the measurement height to be significantly larger than the height of the roughness elements" (Manual BLS 900 3.1.3).

- We have provided more details – page 7 line 213 – 217.

Comment #14: Line 225. Move comma, it should be "(1985),".

- We have made this change (pg .8 line 252).

Comment # 15: Line 238. The end parenthesis after M is missing.

- A parenthesis has been included in equation 5.

Line 239. The kr parameter is not mentioned.

- Kr is now mentioned pg 9 line 266.

Comment # 17:
Line 246. I'm not impressed by this equation, though it has been published. From the name of the parameters you might think that it gives the highest value at Topt but there is no shifting in the equation and it instead gives maximum at (Tmin+Tmax)/2, Topt only works as a scaling parameter.

- We are not sure how to address this comment as the reviewer did not provide an alternative solution. On our part however, we tried other temperature stress functions e.g . that published by Zhang et al.,(1997) but this too did not improve our model simulations.

Zhang, H., Simmonds, L.P., Morison, J.I.L., Payne, D., 1997. Estimation of transpiration by single trees: comparison of sap flow measurements with a combination equation. Agric. For. Meteorol. 87, 155 – 169.

Comment # 18: Line 255. Model name of the thermocouples?

- this is now included – page 9 line 282

Comment # 19: Lines 254-256. I suggest reordering the sentence "… was measured during the ET campaigns using the soil…".

- The sentence has been revised – page 9 line 281 – 282.

Comment # 20:
Line 256-258. As there mostly is hysteresis between soil and air temperature on an annual basis I assume that the regression were applied for shorter periods.

- Yes the regressions were applied on shorter periods.

Comment # 21
Line 273. I can't see that you have mentioned ETo in the M&M.

- This is now included – page 6 line 195 – 196.

Comment # 21:
Line 276. On line 166 you say that you measure SWC at 20 cm, not 0-20 cm.

- We measured the soil water content in the depth range 0 – 20 cm and we have now corrected this in various places throughout the manuscript.

Comment # 22:

Lines 278-282. I don't think this is a correct description. There is an event at about 20 Oct were a shift can be seen and after that they are almost perfectly parallel.

- there was a disturbance(vandalism) at our non- riparian set up and there was a slight shift in the soil water content trend as noted by the reviewer although it appears that the soil water content at the non-riparian actually declined more than at the riparian site in the long-term. However, because of the uncertainty surrounding this trend, we decided to tone down the comparison in the soil water content between the sites.

Comment # 23:
Lines 285-286. Take away "with stem sizes"

- We have removed this phrase.

Comment # 24: Line 287. Take away "at least"

- We have also revised carefully our use of the phrase “at least” throughout the manuscript and we only retain it where we think it is absolutely necessary.

Comment 25: Lines 298-300. It might be an idea to include a figure with a time series of this ratio.

- We agree with this comment and we have actually added a new figure (Fig 5).

Comment # 26: Lines 311-313. Why not give total transpiration?

- Here we have given the total transpiration as suggested (page 11 lines 339 – 340)

Comment #27: Line 369. "there can also be significant"

- We have revised this sentence accordingly.

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Comment #28: Line 383. To really go into this it could be good to make some analysis of canopy conductance.

- Unfortunately, we did not directly measure the canopy conductance of the pines and while inverting the Penman-Monteith equation is an option, the trend will likely be similar to that of the transpiration dynamics as that will depend heavily on the sap flow input data.

Comment # 29:
Line 406. Comma placement "(1994),"

- This has been corrected.

Comment # 30
Lines 421-423. Here it becomes very obvious that a comparison also to indigenous vegetation, at least from literature, is really needed.

- See earlier responses.

Comment # 31: Line 561. "Depth" not "deep". Again you say something else in M&M (line 166).

- We have changed the caption accordingly (pg 19 line 621)

Comment # 32: Line 563. What trees? How were they selected?

- We have revised the caption to Fig 3 and indicated that we dealt with 50 randomly selected trees at each site.

Comment # 33: Table 3. Value of k1? This value means that there is no effect of SWC, I would expect a value of about 3.3.

- Unfortunately, a value of 3.3 for the parameter k1 did not give good model simulations and so we will stick to our optimization results as presented in Table 3.

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REVIEWER # 2

Comment #1:

The paper reports investigations of water use by invasive pines in riparian zones in the western cape province of stH Africa. This is an interesting and topical piece of work and should make a useful contribution. The combination of measurements and modelling is nice although I have some comments on various aspects of this approach below. The conclusion that the riparian pines use more water than the non riparian pines is not altogether surprising. I would think that a paper focussed at water management might have some comments to make on management of the issue and I would like to see some thought put into this. Despite this, in general the paper is well written and concise.

- Thank you for finding our manuscript interesting and relevant to the FEM journal. We have indeed included comments on the implications of pi9ne invasions in indigenous Fynbos vegetation by combining data from this study with that from previous studies on Fynbos (page 14 line 460 – 465).

Comment #2
Ln 29 do you mean invasives rather than invasions?

- We have completed re-phrased the sentence to better present what we mean (pg 2 line 29).

Comment #3: Ln 37. I'm not exactly sure what you mean here, scintolmetry is an energy balance approach

- Here we have now more clearly explained that the scintillometer gives only the sensible heat component of the surface energy balance and an independent energy balance system is required for Rn & G (pg 2 lines 37 – 39).

Comment #4: Ln 41 higher not greater

- We have changed the text accordingly (pg 2 line 42).

Comment #4:
Introduction

82-86 there appears to me an odd contradiction here. On one hand you are saying that CC will increase the rate of spread of the weeds, however evaporative demand will also increase-given that the pines seem quite sensitive to water deficits as outlined in this and other papers, I'm not sure how the two lines of thought are connected. Why will climate change affect the rate of spread of these pines? Further more what aspect of evaporative demand is expected to increase. If temperature increases, a response through VPD might be expected, but Roderik and others (see cites within) have shown that in many locations across the globe evaporation is declining. Either way I think the system is water limited as stated, but I'm a little unclear on the flow of the arguments

Roderick, M.L., Farquhar, G.D., 2004. Changes in Australian pan evaporation from 1970 to 2002. International Journal of Climatology 24, 1077-1090.

- we have extensively revised this section and I hope there is no contradiction any more. Thank for the reference above, but we have also given a more recent reference that is specific to South Africa (pg 3 lines 86-90)

Comment #5: 118 when did the fire occur?

- The fire occurred in March 1992 (page 4 line 125)

Comment #6
You present some results around vegetation structure in but these are not covered in the methods. I think some description around this is important because it impacts on the scaling approaches used in your sapflow data.

- See the responses to reviewer #1 above. We erroneously omitted the details on the tree statistics which we have now corrected.

Comment # 7:
145. The measurement of transpiration is my biggest area of concern in this paper. The replication at the stand level is very low, and this raises some important uncertainties around scaling and interpretation of the sapflow data. Going back to my earlier point related to stand demographics, was sapwood are characterised in these stands or just basal area. You state that stand transpiration was calculated as the weighted sum of water use in each stem size category. In figure 3 there are seven size class categories in the riparian stand and five in the no riparian stand. However ,only 3 and 2 trees were measured in the riparian and non-riparian stands.

- Here see also our responses to reviewer # 1 above.

Comment # 8:

With regard to the scintillometer approach, how confident can you be that you accurately close the energy balance? Sensible heat is average across the path length but Rn and soil heat flux are still point estimates, what impact does this have on estimates of Et?

- This is the general weakness of the scintillometer approach that while good sensible heat flux can be obtained along the transect being investigated, it is difficult to get data on the available energy (Rn – G) which is representative of the entire transect. However, in our study, we used four soil heat flux plates (pg 7 lines 222 – 224) to attempt to average out differences along the transect and we hope this minimized the potential errors.

Comment #9
Results

271 were there differences in rainfall between the two stands?

- No there were no differences in the rainfall because the sites were very close to each other (pg 5 line 137).

Comment # 10: 283 the soil water regimes are similar in winter but not in spring/summer

- Thank you for the suggestion but we have decided to tone down comparisons between the soil water content at the two sites (see comments to reviewer #1).

Comment #11
285-288 Are there age differences playing out here, or are you saying that site is the main driver in the structural differences

- Our selection of the trees was random at both sites (pg 5 line 159) and so any age differences would even themselves out.

Comment # 12:

305 you are assuming the presence of alternative water sources here. While figure two suggests that there is more water available, you cannot make any assumptions about alternative water sources, look to me like it could just e high soil water availability (see Dawson 1991)

- We have been cautious in our interpretation of water sources (see page 13 lines 424-429) and thank you for the reference.

Comment # 13:
Some more clarity around figure our would be good. Are these points averages of tree water on any given day or a collection of individual tree water use/or stand water use. On a terminology front I think the term transpiration should be reserved for water use expressed on a leaf area basis.

- We have explained in the caption of Fig 4 that this is the daily total transpiration at each stand (pg 20 line 627). Regarding the terminology, we understand what the reviewer implies here, but we think that it is a widely accepted assumption that at the daily time step, total sap flow is a good approximation of the daily transpiration. We restricted ourselves to the use of the term "sap flow" rather than "transpiration" when interpreting our hourly data throughout the manuscript.

Comments# 14: Discussion

358 Should leaf thickness increase and 368 there is evidence leaf area does a nice job of predicting excess available water.

- the increase in leaf thickness was observed in the study by Smith et al 1991 and we did not measure this variable in our study.

Comment #15:

370 I think I know what you're getting at here but it is not necessarily the case that because hydraulic conductivity may be higher that sap velocity would be higher.

- We have clarified this statement on page 13 lines 401 to 402 and we hope this now conveys the correct message.

Comment 16:

394 I don't think so, as you point out pines are very conservative in their water use strategies, and at these High vapour pressure deficits would reduce water use to avoid xylem cavitations. The P50 for pines is pretty low so I think it may be a bit of a stretch to link these processes in this paper especially when none of these traits have been measured

- We have extensively revised this argument on page 13 lines 424 to 429.

Lastly we are really grateful for constructive comments from the reviewers and we hope we have addressed most of them satisfactorily and that our manuscript will now be accepted for publication in the Forest Ecology and Management Journal.

Sincerely yours,

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