Sap flow in *Searsia pendulina* and *Searsia lancea* trees established on gold mining sites in central South Africa

Peter Dye[1 *], Vivek Naiken[2], Alistair Clulow[3], Eric Prinsloo[4], Murray Crichton[1] and Isabel Weiersbye[1]

[1]Ecological Engineering and Phytotechnology Programme, School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, P. Bag 3, WITS 2050, Johannesburg, South Africa

[2]CSIR, Natural Resources and the Environment, C/O Agrometeorology, University of KwaZulu-Natal, P. Bag X01, Scottsville 3209, South Africa

[3]Centre for Water Resources Research, University of KwaZulu-Natal, P. Bag X01, Scottsville, 3209, South Africa

[4]CSIR, Built Environment, P.O. Box 320, Stellenbosch 7599, South Africa

* Corresponding Author: peterjdye@gmail.com; Tel: +27 82 3097791: P.O. Box 2205, Hilton 3245, South Africa.

Co-author current email addresses: naikenv@ukzn.ac.za; clulowa@ukzn.ac.za; eprinslo@csir.co.za; murray.crichton@gmail.com; iweiersbye@gmail.com

[2] Present address: Centre for Water Resources Research, University of KwaZulu-Natal, P. Bag X01, Scottsville, 3209, South Africa.

[3] Present address: Agrometeorology, University of KwaZulu-Natal, P. Bag X01, Scottsville, 3209, South Africa.

Abstract

The Witwatersrand Basin Goldfields (WBG) have seen over a century of continuous mining that has generated extensive tailings storage facilities (TSF), together with "footprints" remaining after the residue has been removed for reprocessing or consolidation into larger TSFs. These are now believed to number several hundred and cover a total area of 400-500 km^2. Acid mine drainage (AMD) from these structures is widespread and has resulted in contamination of soils, groundwater and surface water systems. Sustainable and long-term control measures are required to limit environmental contamination. The Mine Woodlands Project, initiated by the University of the Witwatersrand and AngloGold Ashanti Ltd, aims to investigate the use of trees for hydraulic control of mine seepage, as well as contaminant immobilization. A variety of exotic and indigenous tree species was planted in high density stands within site species trials located close to TSFs in the Orkney and Carltonville districts. The aim is to evaluate their survival and growth, as well as water use and contaminant uptake or immobilization.

This paper describes a study of the annual pattern of sap flow rates in two species of indigenous tree (*Searsia lancea* (L. F.) F.A. Barkley and *S. pendulina* (Jacq.) Moffett, comb. nov.) established in plantation form. These species occur naturally in central and western South Africa. Sap flow was monitored continuously over a full year in eight stems representing each species, using the heat ratio version of the heat pulse velocity technique. Plot sap flow was estimated by scaling up according to the number and size of stems, and utilizing functions relating leaf dry mass and leaf area to stem diameter. The deciduous species *S. pendulina* was found to use 591 mm of water over a full growing season, while the evergreen species *S. lancea* was found to use

1 044 mm over a full year. Differences in sap flow patterns between these species are attributed largely to different leaf dynamics. We conclude that *S. lancea* has potential for the hydraulic control of mine seepage water in phytoremediation systems in the WBG.

Keywords: Witwatersrand Basin Goldfields, acid mine drainage, phytoremediation, *Searsia lancea*, *Searsia pendulina*, sap flow, hydraulic control

1. Introduction

The Witwatersrand Basin Goldfields (WBG) comprise an area of approximately 25 000 km^2 in north central South Africa. Gold deposits were discovered in 1886, and have been mined continuously since then, yielding approximately 50 000 tonnes of gold, equivalent to about 31% of all gold ever mined anywhere throughout history (McCarthy and Rubidge, 2005). Gold mines are located along the northern and western margins of this basin. Tailings are pumped in the form of a slurry and deposited on large unlined tailings storage facilities (TSF). These TSFs number several hundred (many are now being reprocessed and consolidated into fewer larger dumps) and total approximately 400 - 500 km^2 in area (Marsden, 1986; Blight, 2011). After more than a century of mining, they contained an estimated 6 billion tonnes of tailings (Blight, 2011), which was estimated to include 430 000 tonnes of low grade uranium (Winde et al., 2004) and 30 million tonnes of sulphur (Witkowski and Weiersbye, 1998). Additional gold tailings are produced in the WBG at an estimated rate of 105 million tonnes per annum (Chamber of Mines of South Africa, 2004).

Many years of acid mine drainage (AMD) from the saturated core of gold tailings dams has resulted in artificially elevated groundwater levels and extensive contamination of soils, streams, sediments and groundwater (Rudd, 1973; Funke 1990; Coetzee 1995; Hodgson et al., 2001; Rösner et al., 2001; Naiker et al., 2003; Coetzee et al., 2004; Winde et al., 2004; Tutu, 2005; Sutton et al., 2006; Coetzee and Winde, 2006; Chevrel et al., 2008). Levels of contaminants sometimes exceed environmental standards (Coetzee and Venter, 2005; Coetzee and Winde, 2006) and therefore pose a potential danger to humans, farm animals, and both crop and natural ecological systems. Public awareness of the pollution threat is growing as the media increasingly draw attention to pollution threats (Earthlife Africa, 2011). Many mines are nearing the end of their lives, and closure planning is assuming more importance. A prerequisite of Government closure certificates is that sustainable and long term control measures are in place to limit environmental contamination. Engineering solutions are costly and unlikely at this stage to offer sustainable long term answers by themselves. Phytoremediation measures are far less costly (Weiersbye, 2007), and experience globally has shown that this approach may be effective and sustainable.

The Mine Woodlands Project (MWP) was initiated by the University of the Witwatersrand and Anglogold Ashanti Ltd in 2001, with additional funding and support from the South African Department of Trade and Industry (THRIP programme) and NRF, and in-kind support from the DWAF: Directorate of Participatory Forestry. The intention of this phytoremediation research programme is to show the effectiveness of woodlands in taking up contaminants from soils and groundwater, and reducing or preventing the spread of mine drainage water from tailings dams, to provide a sustainable, low cost and long term solution to the pollution threat. As an example of the potential of trees to take up contaminants, research has shown that the hyper-accumulator species *Tamarix usneoides* can take up large quantities of salt which is exuded through salt glands and deposited on the leaf surface (Wilson and Mycock, 2014). Periodic harvesting of stems with their foliage will allow the contaminants to be disposed of at a safe site.

The potential for deep rooted indigenous trees and shrubs to exert hydraulic control and minimize the lateral flux of contaminants in groundwater is the subject of this paper. It is a well-established technology (ITRC, 2009; Landmeyer, 2011) that relies on the abstraction of water and ions by the living plant, and the phytoimmobilization or sequestration of contaminants in the rhizosphere and biomass, respectively. Suitable species of trees planted at sufficiently high densities are able to increase the rate of evapotranspiration (ET), thereby reducing the water contents in soil and the volume of groundwater (Bari and Schofield, 1992; Schofield, 1992; Salama et al., 1994; Raper, 1998). Substantially higher rates of ET following establishment of trees is predicted for sites in the WBG. The original vegetation surrounding most TSFs is dominated by seasonally dormant, shallow rooted grasslands, which are known to be relatively low water users (Dye et al., 2008). By replacing grasslands with deep rooted trees with higher leaf areas and shorter or no seasonal dormancy, ET can be greatly increased. There is much evidence from South African hydrological catchment experiments (Scott, 2000) and from global reviews of such land use change (Bosch and Hewlett, 1982; Zhang et al., 1999; Farley et al., 2005) to show that ET will increase when grasslands are replaced by closed canopy tree species, especially where water availability is high (Zhang, 1999). Woodland establishment is expected therefore to reduce the flow of water and contaminants through shallow aquifers and saturated soil horizons into adjacent lands and surface drainage channels.

An important aim of the MWP has been to test the suitability of a range of exotic and indigenous tree species established in high density woodland plots at different site types. Fastest growth and canopy development is shown by several *Eucalyptus* species, but their use for phytoremediation is hampered by legislation and negative public opinion towards alien tree species. The use of indigenous tree species is therefore an important alternative that requires investigation. Little information is available on the water use characteristics of indigenous tree species in South Africa.

Two indigenous tree species belonging to the *Searsia* genus (Family Anacardiaceae; formerly in the genus *Rhus,*) have demonstrated good survival and growth. S. *lancea* (L.f.) F.A. Barkley

(Karee) is an evergreen, generally multi stemmed tree (Coates-Palgrave, 2002) that is widely planted in mining sites in the WBG. It occurs extensively throughout the relatively dry central areas of South Africa, but shows a preference for drainage lines and riverbanks. *S. pendulina* (Jacq.) Moffett is a semi deciduous to deciduous tree that occurs along riverbanks and wetlands in a narrow band that follows the Orange River from the Free State province to Namibia. This species (known as White Karee, Willow Karee, River Karee) is multi stemmed, and reaches 10 m in height. Both species appear well able to tolerate a wide variety of mine sites (Weiersbye *et al.*, 2006; Weiersbye and Witkowski, 2007), and show tolerance to AMD polluted groundwater. A previous study of sap flow in three size classes of *S. lancea* (Dye et al., 2008) suggested an annual water use rate that is intermediate between grasslands and *Eucalyptus* stands. However, the sample trees occurred in low density woodland. The relevance of the results to high density, closed canopy stands with higher levels of competition among the trees therefore requires investigation.

The purpose of this study was to quantify the total annual sap flow within high density stands of these two species in order to assess their potential for hydraulic control of mine seepage water on mining sites.

2. Site and trial descriptions

Sap flow measurements took place within two site-species trials. The *S. pendulina* plot is situated within the Mispah site-species trial (26^o 59’ 20.91’’S; 26^o 46’ 30.83’’E) at Vaal River, while the *S. lancea* plot is situated in the Madala site-species trial (26^o 25’ 55.18’’S; 27^o 20’ 05.03’’E) at West Wits. These trial sites are described below.

2.1 Mispah trial (*S. pendulina*)

This trial is situated approximately 154 km southwest of Johannesburg (Figure 1). The climate of the region (Table 1) is warm temperate, and characterized by summer rainfall with high summer temperatures, and frequent winter frosts (Schultze, 1997; Mucina and Rutherford, 2006).

Although most of the vegetation growing in the Vaal River mining area is degraded grassland transformed by mining, the natural vegetation type is Vaal Reefs Dolomite Sinkhole Woodland (Gh12), a grassland biome vegetation subunit found in North West and Free State provinces within an altitudinal range of 1 280 to 1 380 metres above sea level (M.A.S.L.) (Mucina and Rutherford, 2006). This vegetation type supports a grassland woodland complex characterized by clumps of woodland that form on dolomite sinkholes. The dominant tree taxa include *S. lancea*, *Vachellia* (formerly *Acacia*) *erioloba* and *Celtis africana* (Mucina and Rutherford, 2006).

The soils at the Mispah trial are deep, red brown, well drained sandy clay loams to sandy loams (Hutton, Hayfield family) derived from highly weathered, largely chert free Malmani Formation dolomite (Herbert, 2003). The equivalent FAO classification is Rhodic Ferralsol. The effective rooting zone observed in deep soil pits is 3.5 to 4.0 m. This overlies weathered dolomite stretching to 10 m below ground (Vivier et al., 2004). Two boreholes (VRM51 and VRM58) situated close to the trial margins revealed a water table at 10.8 and 9.9 metres below ground level respectively in January 2007.

The Mispah site-species trial was established in January 2003. It includes 18 tree species, of which 10 are indigenous. Sixty three seedlings were planted in each plot in a 7 by 9 block, and at a spacing of 3 by 2.5 m (1 333 stems per hectare). Blanking occurred to replace those trees not surviving the first growing season. Four sample trees were selected within plot 21 based on their healthy growth, absence of fire damage scars and uniformity of canopy cover in adjacent trees.

2.2 Madala trial (*S. lancea*)

The Madala site-species trial at West Wits is situated approximately 75 km WSW of Johannesburg and 7 km south of the town of Carltonville (Figure 1). Salient climatic parameters at this site are shown in Table 1. The natural vegetation in the area is classified as Gauteng Shale Mountain Bushveld (SVcb10, Mucina and Rutherford, 2006), a savanna biome vegetation subunit found in the Gauteng and North West provinces within an altitudinal range of 1 300 to 1 750 M.A.S.L. It is typically characterized by short (3-6 m tall) semi open thickets comprising a variety of tree species surrounded by grasslands.

The trial site is situated within the Varkenslaagte catchment, and is heavily influenced by several up slope TSFs that cause a strong flow of AMD to move laterally through the soils and sub soils to emerge at the drainage channel. This water is characterized by low pH, elevated concentrations of sulphates, sodium, chlorides, iron, manganese and cadmium (Vivier et al., 2001). A brown, sandy clay soil (0-1 m) is underlain by weathered, fractured shale that extends to approximately 8-10 m below the surface (Vivier et al., 2004). This material is relatively soft and could potentially be penetrated by tree roots. The hydraulic conductivity of the soil and deeper weathered shale zone is reported to be 0.25 and 0.1 m d^{-1}, respectively. Deeper fracture zones are more permeable and directly linked with tailings dam seepage, creating artesian conditions in several of the boreholes in the area. Total lateral flow over a 1 m front and to a depth of 8 m is estimated as 0.016 m^3 d^{-1} (Vivier et al., 2004).

The trial was established in January 2003 and comprises 80 plots. Each was planted to one of 18 different tree species, 10 of which are indigenous. Again, 63 trees were planted per plot at a spacing of 3 by 2.5 m (1 333 stems per hectare). Four *S. lancea* sample trees were selected from plot 28, using the same criteria adopted in the *S. pendulina* plot. Potted *S. lancea* were transplanted into plots in January 2003. The *S. lancea* were all propagated from genotypes originating from Upington, Northern Cape, South Africa (Herbert, 2003). A large proportion of the plot was subsequently damaged by fire. The sample trees were selected from a portion of the plot where these trees and a surrounding row of buffer trees escaped serious damage.

3. Materials and methods

3.1 Sap flow measurements

Four adjacent trees forming a square were selected for sampling near the centre of each plot. In each tree, two healthy stems with the largest stem diameters were chosen for sap flow measurement. In the *S. pendulina* plot at the Mispah trial, probes were implanted on 20 October 2008 when the trees were aged 5 years and 10 months. Sap flow data were analyzed for a complete year from 21 October 2008 to 20 October 2009. In the *S. lancea* plot at the Madala trial, the same stem sampling and probe implantation procedure was adopted. Probes were implanted on 12 March 2009. Sap flow data were recorded from 13 March 2009 to 12 March 2010. The age of the trees at the start of measurements was 6 years and 3 months.

The heat ratio version of the heat pulse velocity (HPV) technique (Burgess et al., 2001) was used to record hourly sap flow rates in the eight sample stems at each site. Each set of probes consisted of two thermocouple (TC) probes and a line heater probe. Two sets of probes were implanted in each sample stem. These were implanted radially into the sapwood at two different heights, orientated approximately 90^{O} from each other. The line heaters were made from 1.8 mm outside diameter stainless steel tubing, enclosing a constantan filament. TC probes were situated parallel to, and 5 mm above and below the line heater. These probes (consisting of type T copper constantan thermocouples embedded in 2 mm outside diameter PTFE tubing) were inserted into the upper and lower holes to depths of 8 or 15 mm below the stem surface (5 and 12 mm below the bark cambium interface), to sample the radial variation in sap flux density. All drilling was performed with the drill bit projecting through a 30 mm thick steel drill guide firmly strapped to the tree, to ensure that the holes were as close to parallel as possible. Mean bark thickness was found to be 3 mm.

All probes were connected to CR10X data loggers via AM16/32 multiplexers (Campbell Scientific, Logan, UT). The logger was programmed to initiate a heat pulse every hour, and to record pre pulse and post pulse temperatures (Burgess et al., 2001). HPV was calculated using the heat ratio method (Burgess et al., 2001). These readings were corrected for wound widths (a mean wound width of 3 mm was assumed, based on visual examination of stem wounds). Wound correction coefficients described by Swanson and Whitfield (1981) were used for this correction. Wound corrected HPV was converted to sap flux density (Marshall, 1958), using sapwood density and sapwood moisture fractions recorded for each species. From these sap flux densities, whole tree sap flow was calculated by summing the mean stem sap flux density multiplied by the sapwood area of each sapwood zone. Based on visual examination of stem cross sections, sapwood thickness was assumed to be a constant 2 cm. A constant sapwood area was assumed over the 12 month monitoring periods, since radial stem growth was observed to be low.

In certain species, the heat ratio version of the HPV technique is susceptible to “spiking” during periods of high sap flow, especially between mid morning and mid afternoon. This phenomenon was observed in both species. A Gaussian smoothing function (Data Curve Fit Creator) was used to reduce the influence of these spikes. This function was run on data recorded from 05h00 to 19h00 each day. A sigma value (standard deviation) of 2 was specified throughout. Extensive testing of the smoothed outputs showed them to successfully preserve the trend in daily pattern of sap flow under a wide variety of weather conditions and times of year. A high degree of consistency in these patterns was retained among all the stems following the smoothing process. Periods of missing data were in filled by calculating daily reference evaporation (Allen et al., 1998) for the whole year, and using “crop coefficients” calculated at the start and end of gaps to estimate daily whole plot sap flow. Daily weather data from Klerksdorp and Carltonville were obtained from the South African Weather Service for the reference evaporation calculations. Solar radiation and wind speed were recorded at an automatic weather station (26^{o} 57’ 46.68” S; 26^{o} 42’ 56.89” E) situated 6.5 km from the Vaal River Mispah trial.

3.2 Scaling up to the whole plot

Only two sample stems were chosen from each tree, and these had to be the larger ones to accommodate the HPV probes. To estimate the total sap flow from each plot, the contribution of the smaller unsampled stem size classes had to be estimated. This was accomplished by scaling down from the larger sampled stems to the smaller unsampled stems according to their differences in leaf mass. This assumes that differences in leaf mass and area are the main determinants of variation in total sap flow in even aged stems of different sizes growing under the same conditions (Wullschleger et al., 1998; Čermák et al., 2004). This assumption was made in light of the relatively open canopy structure of both species, which allows most of the stems of these young trees to expose their foliage to a similar degree within the tree canopy. Large differences in ambient light, humidity and temperature are therefore not expected to occur among leaves associated with different stem sizes.

The relation between stem diameter at 30 cm above ground and dry leaf mass was obtained in a separate destructive study of allometric relationships in plots of *S. pendulina* and *S. lancea* in the Mispah trial (Crichton, 2010). This study took place from 24 to 27 March 2010 before leaf senescence became pronounced in *S. pendulina*. Stem diameter at 30 cm proved to be highly correlated to dry leaf mass in both species.

In each sap flow plot, all stem diameters at 30 cm were recorded within a sub plot that included all stems showing minimal fire scars. The *S. pendulina* sub-plot included 20 trees and 148 stems in an area of 150 m^2, while the *S. lancea* sub-plot included only the four HPV sample trees comprising 29 stems in an area of 30 m^2. Stems in each sub-plot were divided into five size classes. Mean sap flow in each class was estimated in one of two ways. If sap flow measurements were available for one or more stems falling in the size class, then the mean sap flow measurement was applied to that class. If no sap flow measurements were available for stems in the size class, then sap flow was estimated as a fraction of the mean sap flow rate in the class represented by the highest number of sap flow stems. This fraction was determined by the ratio of the total dry leaf mass between the two size classes.

Measurement of specific leaf area (projected leaf area per unit of dry mass) for each species was described by Crichton (2010). Sub-samples of fresh leaves were obtained from each of ten sampled trees per species, sealed in plastic bags and refrigerated whilst transported to the laboratory. The total area of each subsample was measured using a portable leaf area meter (CI-202 Portable Leaf Area Meter, CID Inc., 4901 NW Camas Meadows Drive, Camas, WA 98607, USA). Subsamples were then oven dried at 60°C until constant mass.

3.3 Weather data

Daily weather data were required to calculate reference ET to aid in the interpretation of daily variation in sap flows, and also to provide a basis for patching data gaps in the *S. lancea* data record. Mean day time temperatures, relative humidity and wind speed, and daily total rainfall were obtained from the South African Weather Service. Data used for the Mispah trial site was taken from a weather station in Klerksdorp (0436204 1) situated 18.4 km away. Data used for the Madala trial site was recorded at a station (0474680 9) in the town of Carltonville, which is situated 11.3 km away. Solar radiation was recorded at an automatic weather station (26^{o} 57’ 46.68” S; 26^{o} 42’ 56.89” E) situated 6.5 km from the Mispah trial site at Vaal River.

4 Results

4.1 *Searsia pendulina*

Table 2 shows stem diameters, sapwood areas, leaf dry mass, specific leaf area and leaf area for each stem used for sap flow measurement. Figure 2 illustrates the relation found for this species between stem diameter at 30 cm and dry leaf mass. Table 3 shows the five stem diameter classes and the number of stems in each class used for sap flow measurement. Dry leaf mass is estimated for each mean stem size class, and this is expressed as a fraction of the class with the most measured stems. Moving to the sub plot scale, the total leaf mass was estimated by scaling the mean tree leaf mass in each size class by the number of stems in that size class. The total leaf area in each size class was then estimated from the specific leaf area (8.9 m^2 kg^{-1}) determined for the species (Crichton, 2010). Total leaf area index (1.69) was calculated by dividing the total estimated sub plot leaf area by the ground area.

Figure 3 shows daily estimates of sap flow for the entire *S. pendulina* sub-plot. Daily sap flow is relatively low in early October when new leaves have just emerged, but have yet to expand to their full size. Daily sap flow increases rapidly to peak at the end of December when leaves are fully formed and maximum day length occurs. Thereafter, daily flow rates decline steadily during the second half of summer and into autumn and early winter. Leaf drop is not significant until April. The earlier decline is attributed to reduced day lengths, but also to significant leaf spotting and predation by insects which reduce the efficiency of leaf transpiration. Daily sap flow frequently declines during periods of rainfall when lower temperatures and solar radiation, and higher humidity reduce the evaporative power of the air (Allen et al., 1998). Daily variation declines into autumn and winter as days become sunny and dry. The dry Spring of 2009 illustrates how sap flow remains low at this time of year until rainfall occurs to initiate further canopy development and higher rates of sap flow. Total sap flow over the whole growing season was estimated to be 591 mm. Rainfall over the same period amounted to 715 mm.

4.2 *Searsia lancea*

Table 4 shows stem diameters, sapwood areas, leaf dry mass, specific leaf area and leaf area for each *S. lancea* stem used for sap flow measurement. Stem 4 yielded poor quality HPV data and so had to be omitted from the analysis. Table 5 shows the five stem size classes defined to cover the range of stem diameters observed in the *S. lancea* plot. Dry leaf mass per mean stem size was estimated from the stem diameter at 30 cm, using the relation shown in Figure 4. Total leaf area per mean stem was calculated using the specific leaf area of 8.7 m^2 kg^{-1} recorded for this species (Crichton, 2010). These were scaled up to the sub plot, taking into account the total number of stems in each size class. Leaf area index was estimated to be 3.57.

Figure 5 shows the annual pattern of daily sap flow for *S. lancea*. A major difference to the *S. pendulina* pattern of daily sap flow is the continued sap flow during winter. Winter rates are lower than summer rates, reflecting shorter day lengths and lower potential evaporation, but nevertheless average about 2 mm per day. This is a primary reason for the higher *S. lancea* annual sap flow total (1 044 mm) than for the deciduous *S. pendulina* (591 mm). Daily sap flow is again responsive to periods of wet and overcast weather, and closely tracks ET_0. In contrast to *S. pendulina*, highest daily sap flow occurred in the second half of summer. During a site visit in late September, it was observed that leaves were noticeably yellow, spotty and significantly damaged by insects. Replacement of these leaves by a new flush of leaves is believed to explain the lower sap flow rates at this time of year. Rainfall over the sap flow monitoring period equalled 772 mm. Transpiration thus exceeded rainfall by 272 mm. This suggests significant utilization of subsurface mine water originating from up-slope tailings dams and passing through the site.

5 Discussion

The evergreen *S. lancea* was clearly capable of a higher annual sap flow than the deciduous *S. pendulina*, largely due to being able to maintain green leaves and transpiration throughout the year. The additional evaporative losses from wet tree canopies, understory plants and soil surface will add to the annual ET from both plots, but are not expected to greatly change the annual evapotranspiration difference between these two species. A higher LAI in the *S. lancea* plot in summer is likely to lead to higher canopy rainfall interception, but this may be partially compensated by a higher rate of evaporation from soil and understory plants beneath the *S. pendulina* canopy with lower LAI. The significance of these evaporative processes to total evapotranspiration is limited by the fact that rainfall generally falls in relatively large and infrequent storms, reducing the number of wetting up events, and the proportion of rainfall lost to direct evaporation.

It is important to emphasize that the two sites were very different. The Madala site at West Wits is characterized by relatively shallow water tables and strong summer time lateral flow of mine water. Water availability to the trees is believed to remain relatively high throughout the year, promoting significant sap flow over all seasons. The Mispah site at Vaal River has groundwater at 10 m below the surface, which is unlikely to be available to young trees. However, the *S. pendulina* at this site is strongly deciduous, and much of the annual transpiration coincides with summer rains, and so we believe that annual sap flow is more constrained by leaf area (a low LAI and a short period of maximum leaf area) than by soil water availability. The sap flow results showed that poor rains in spring of 2009 delayed the build up of leaf area (Figure 3). It is therefore likely that good rains well distributed over the growing season will result in a somewhat higher annual sap flow in this species. Overall, however, annual sap flow remains severely constrained by the short period of optimal leaf area in mid summer and the leafless state of the trees in winter.

Results suggest that *S. pendulina* has little potential for hydraulic control of mine seepage, despite its growth rate being amongst the highest of the indigenous tree species occurring in the trials. By contrast, *S. lancea* appears to be a relatively high water user and is potentially useful for the management of excess mine water. The annual total sap flow of 1 044 mm is similar to an earlier estimate of annual sap flow (mean of 1 096 mm) obtained in widely spaced trees of this species over a 2 m deep water table within a natural woodland at Vaal River (Dye et al., 2008). These figures are substantially higher than grassland ET estimated for the area (566 mm), although somewhat below the rotation mean ET of 1 270 mm which was simulated for a *Eucalyptus camaldulensis* stand in a similar environment (Dye, 2002). Deep soil pits in the Mispah trial plots at Vaal River have shown that *S. lancea* is capable of developing a deep root system below 3 m from the surface, a very useful attribute in trees established to utilize groundwater. The relatively young stand investigated in this study was found to have an LAI of 3.57. Older trees are characterized by well developed dense canopies, and appear to tolerate competition from neighbouring trees in dense stands. A higher peak LAI is therefore likely to develop in time as the trees continue to grow and mature, and a higher annual water use may be attained in older stands. Thus, further measurements of water use by older trees are required to gain better perspective of the water use pattern over the whole growth cycle of these species.

Such information will permit calculation of the approximate area of woodland required to match estimated seepage rates from TSFs. For example, one can assume (for non-riparian sites) that the difference between annual sap flow and annual rainfall represents the amount of groundwater utilized. In the *S. lancea* plot, this amounts to 272 mm y^{-1}, or 2 720 m^3 ha^{-1} y^{-1}. Considering a hypothetical example of a 150 ha TSF releasing 170 000 m^3 y^{-1} of seepage water, the required woodland area would be 63 ha. Trees would need to be established over contaminant plumes where tree roots can readily access water tables.

The heat balance method of measuring sap flows was found to be practical for monitoring transpiration in *S. pendulina* and *S. lancea* grown in small plots. Stem probes could only be implanted in the larger stems, and so the range in size of measurable stems was limited. Sufficient equipment was available for eight probe sets per species. A sampling intensity of 5-12 sap flow measurements is common in sap flow studies within homogeneous, monospecific stands of even aged trees and regular spacing (Granier, 1987; Olbrich et al., 1993; Vertessy et al., 1997; Dye et al., 2001). As the *Searsia* trees approach maturity, however, one can expect a higher proportion of larger, measurable stems as well as greater competition among trees, leading to a wider range of measurable stem size, and greater variation in such environmental constraints such as canopy exposure to sun, tree water status and leaf area. Future studies should follow guidelines by Čermák et al. (2004) and Hatton (1995) in deciding on an adequate sample size of stems.

Attention also needs to be paid to the question of measurement scale in follow on studies. There is great variation in soil type, depth to contaminant groundwater plumes, groundwater quality, distance from contaminant sources, stand age and canopy structural characteristics, ground disturbance related to mining, rainfall distribution, salt accumulation and many other factors potentially affecting tree water use. A technique is required that will provide the larger scale picture and permit routine monitoring of water use over long tree maturation cycles. Larger tree blocks have been planted (and are also planned for the near future) at Vaal River and West Wits, and these will permit the use of remote sensing techniques such as SEBS, METRIC and SEBAL to quantify ET over multi-year time periods. Long term ET estimation must be linked to trends in depth to groundwater as recorded in extensive networks of boreholes at Vaal River and West Wits to demonstrate the degree to which hydraulic control can be achieved by planting trees.

6 Acknowledgements

We are grateful to AngloGold Ashanti Ltd for their long term support of the Mine Woodlands Project in general, and this study in particular. The South African Department of Trade and Industry and the National Research Foundation are also gratefully acknowledged for their support of the project. The research team was wholly responsible for the design, collection, analysis and interpretation of data, as well as the writing and submission of the manuscript to SAJB. AngloGold Ashanti Ltd granted approval to submit the manuscript to SAJB. The South African Weather Service is thanked for supplying weather station data. Mr B. Oageng provided valuable support in the field.

7 References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations Rome, Italy. 315 pp.

Bari, M.A., Schofield, N.J., 1992. Lowering of a shallow, saline water table by extensive eucalypt reforestation. Journal of Hydrology 133, 273-291.

Blight, G., 2011. Mine waste: A brief overview of origins, quantities, and methods of storage. In: Letcher, T. and Vallero, D. (Eds.), Chapter 5. Waste - A Handbook for Management. Elsevier. pp.77-88.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, Journal of Hydrology 55, 3-23.

Burgess, S.S.O., Adams, M.A., Turner, N.C., Beverly, C.R., Ong, C.K., Khan, A.A.H., Bleby, T.M., 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiology 21, 589-598.

Čermák, J., Kučera, J., Nadezhdina, N., 2004. Sap flow measurements with some thermodynamic methods, flow integration within trees and scaling up from sample trees to entire forest stands. Trees 18, 529-546.

Chamber of Mines of South Africa, 2004. Department of Mineral and Energy Affairs. Annual Report 2004.

Chevrel, S., Croukamp, L., Bourguignon, A., Cottard, F., 2008. A remote sensing and GIS based integrated approach for risk based prioritization of gold tailings facilities – Witwatersrand, South Africa, in: Fourie, A.B., Tibbett, M., Weiersbye, I.M., Dye, P.J. (Eds), Proceedings of the Third International Seminar on Mine Closure, Mine Closure 2008, 14–17 October 2008, Johannesburg, South Africa, Australian Centre for Geomechanics, Perth, ISBN 978 0 9804185 6 9, pp. 639-650.

Coates-Palgrave, M., 2002. Keith Coates-Palgrave Trees of Southern Africa, Edn 3, imp 4, Random House Struik (Pty) Ltd, Cape Town.

Coetzee, H., 1995. Radioactivity and the leakage of radioactive waste associated with the Witwatersrand gold and uranium mining. International Conference on Uranium Mining and Hydrogeology, Freiberg, Germany.

Coetzee, H., Wade, P., Winde, F., Ntsume, G., Horstmann, U., Rademeyer, M., 2004. An assessment of current and future water pollution risk with application to the Mooirivierloop (Wonderfontein*).* Council for Geosciences (CGS), Pretoria, South Africa.

Coetzee, H., Venter, J., 2005. Contamination of wetlands by Witwatersrand gold mines - Processes and the economic potential of gold in wetlands. Report No. 2005 0106, Council for Geosciences (CGS), Pretoria, South Africa.

Coetzee, H., Winde, F., 2006. An assessment of sources, pathways, mechanisms and risks of current and potential future pollution of water and sediments in gold mining areas of the Wonderfonteinspruit catchment: WRC Report No. 1214/1/06, Water Research Commission, Pretoria, South Africa.

Crichton, M., 2010. The potential of stands of *Searsia lancea*, *S. pendulina* and *E. dunnii* to enhance evapotranspiration and consume acid mine drainage from slimes dams on the Highveld. B.Sc. Honours research report, University of the Witwatersrand, Johannesburg, South Africa.

Dye, P.J., Moses, G., Vilakazi, P., Ndlela, R., Royappen, M., 2001. Comparative water use of wattle thickets and indigenous plant communities at riparian sites in the Western Cape and KwaZulu-Natal. Water SA 27, 1-10.

Dye, P.J., 2002. 3 PG simulation of growth and water use of *Eucalyptus camaldulensis* in the Mahem Spruit catchment, Welkom. Report to the University of the Witwatersrand, Johannesburg, Anglogold Ashanti Ltd and FreeGold. Report ENV D C 2002 016, CSIR, Pretoria, South Africa.

Dye, P.J., Jarmain, C., Oageng, B., Xaba, J., Weiersbye, I.M., 2008. The potential of woodlands and reed beds for control of acid mine drainage in the Witwatersrand Gold Fields, South Africa, in: Fourie, A.B., Tibbett, M., Weiersbye, I.M., Dye, P.J. (Eds), Proceedings of the Third International Seminar on Mine Closure, Mine Closure 2008, 14–17 October 2008, Johannesburg, South Africa. Australian Centre for Geomechanics, Perth, ISBN 978 0 9804185 6 9, pp. 639-650.

Earthlife Africa, 2011. Civil society demands action on acid mine drainage. Accessed online at: http://earthlife.org.za/2011/01/civil-society-demands-action-on-acid-mine-drainage/. (last accessed 22 August 2016).

Farley, K.A., Jobbagy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology 11, 1565-1576.

Funke, J.W., 1990. The water requirements and pollution potential of South African gold and uranium mines. WRC Report No. KV9/90, Water Research Commission, Pretoria, South Africa.

Granier, A. 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiology 3, 309-320.

Hatton, T.J., Wu, H.I., 1995. Scaling theory to extrapolate individual tree water use to stand water use. Hydrological Processes 9, 527-540.

Herbert, M., 2003. Mine Woodlands Project: Experimental description, design and field layout: Site species research programme: 2002/03. Fractal Forest Africa.

Hodgson F.D.I., Usher, B.H., Scott, R., Zeelie, S., Cruywagen, L.M., De Necker, E., 2001. Prediction techniques and preventative measures relating to the post operational impact of underground mines on the quality and quantity of groundwater resources. WRC Report no. 699/1/01, Water Research Commission, Pretoria, South Africa.

ITRC (Interstate Technology and Regulatory Council), 2009. Phytotechnology technical and regulatory guidance and decision trees, revised. PHYTO 3. Washington, D.C.: Interstate Technology and Regulatory Council, Phytotechnologies Team, Technical Regulatory Update. www.itrcweb.org (last accessed 6 October 2015).

Landmeyer, J.E., 2011. Introduction to phytoremediation of contaminated groundwater: historical foundation, hydrologic control, and contaminant remediation. Springer Dordrecht, Heidelberg, London, New York.

Marsden, D.D., 1986. The current limited impact of Witwatersrand gold mine residues on water pollution in the Vaal River system. Journal of the Southern African Institute of Minerals and Metallurgy 86, 481-504.

Marshall, D.C., 1958. Measurement of sap flow in conifers by heat transport. Plant Physiology 33, 385-396.

McCarthy, T., Rubidge, B., 2005. The story of earth and life. Struik Publishers, Cape Town, South Africa.

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

Naiker, K., Cukrowksa, E., McCarthy, T.S., 2003. Acid rock drainage arising from gold mining activity in Johannesburg, South Africa & environs. Environmental Pollution 122, 29-40.

Olbrich, B.W., Le Roux, D., Poulter, A.G., Bond, W.J., Stock, W.D., 1993. Variation in water use efficiency and ^{13}C levels in *Eucalyptus grandis* clones. Journal of Hydrology 150, 615-633.

Raper, G.P., 1998. Agroforesty water use in mediterranean regions of Australia. Water and salinity issues is hydrology, no. 2, Rural Industries Research and Development Corporation, Canberra, Australia.

Rösner, T., Boer, R., Reyneke, R., Aucamp, P., Vermaak, J., 2001. A preliminary assessment of pollution contained in the unsaturated and saturated zone beneath reclaimed gold mine residue deposits. WRC, Report No. 797/1/01, Water Research Commission, Pretoria, South Africa.

Rudd, R.T., 1973. The impact of slimes dam formation on water quality and pollution. Journal of the Southern African Institute of Mineral and Metallurgy. December 1973, pp 184-192.

Salama, R.B., Bartle, G.A., Farrington, P., 1994. Water use of plantation *Eucalyptus camaldulensis* estimated by groundwater hydrograph separation techniques and heat pulse. Journal of Hydrology 156, 163-180.

Schofield, N.J., 1992. Tree planting for dryland salinity control in Australia. Agroforestry Systems 20, 1-23.

Schulze, R.E., 1997. Climate, in: Cowling, R.M., Richardson, D.M., Pierce, S.M. (Eds.), Vegetation of Southern Africa. Cambridge University Press, Cambridge, UK, pp. 21-42.

Scott, D.F., Prinsloo, F.W., Moses, G., Mehlomakulu, M., Simmers, A.D.A., 2000. A re analysis of the South African catchment afforestation experimental data. WRC Report No. 810/1/00, Water Research Commission, Pretoria, South Africa.

Sutton M.W., Weiersbye, I.M., Galpin, J.S., Heller, D., 2006. A GIS based history of gold mine residue deposits and risk assessment of post mining land uses on the Witwatersrand Basin, South Africa, in: Fourie, A.B., Tibbett, M. (Eds.), Mine Closure 2006, Proceedings of the 1st International Seminar on Mine Closure, Australian Centre for Geomechanics, Perth, ISBN 0 9756756 6 4, pp. 667-678.

Swanson, R.H., Whitfield, D.W.A., 1981. A numerical analysis of heat pulse velocity theory and practice. Journal of Experimental Botany 32, 221-239.

Tutu, H., 2005. Determination and geochemical modelling of the dispersal of uranium in gold mine polluted land on the Witwatersrand. PhD thesis, University of the Witwatersrand, Johannesburg, South Africa.

Vertessy, R.A., Hatton, T.J., Reece, P., O’Sullivan, S.K., Benyon, R.G., 1997. Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. Tree Physiology 17, 747-756.

Vivier, J.J.P., Myburgh, J.A., Pretorius, S.J., van Rensburg, H.J., De Jager, F., 2001. Regional geohydrological assessment to determine the status and impact of groundwater pollution at the Anglo Gold West Wits operations. Project report GC/R/01/10/10, Southern Africa Geoconsultants, Pretoria, South Africa.

Vivier, J.J.P., Wiethoff, A., Kriek, C., 2004. Anglogold Vaal River and West Wits operations – Development of monitoring boreholes for the Wits Anglogold Woodlands Project. Technical report AG/R/04/09/14, Africa Geo Environmental Services, Pretoria, South

Africa.

Weiersbye, I.M., Witkowski, E.T.F., Reichardt, M. 2006. Floristic composition of gold and uranium tailings dams and adjacent polluted areas, on South Africa’s deep level mines. Bothalia 36, 101-127.

Weiersbye, I.M., 2007. Global review and cost comparison of conventional and phyto technologies for mine closure, in: Fourie, A.B., Tibbett, M., Wiertz, J. (Eds), Mine Closure 2007, Proceedings of the 2nd International Seminar on Mine Closure, Santiago, Chile, pp 13-29.

Weiersbye, I.M., Witkowski, E.T.F., 2007. Impacts of acid mine drainage on the regeneration potential of highveld phreatophytes, in: Bester, J.J., Seydack, A.H.W., Vorster, T., Van der Merwe, I.J., Dzivhani, S. (Eds), Multiple use management of natural forests and woodlands: policy refinements and scientific progress, Natural Forests and Savanna Woodlands Symposium IV, Port Elizabeth, South Africa, 15-18 May 2006. Symposium Proceedings, Department of Water Affairs and Forestry, Pretoria, South Africa, pp. 224-237.

Wilson, H. T. and Mycock, D., 2014. The ultrastructure of the salt glands of *Tamarix usneoides* E. Mey ex Bunge and its implications for phyto-extraction. IGCP/SIDA Projects 594 and 606, Closing workshop, Prague, Czech Republic, 195-199.

Winde, F., Wade, P., Van der Walt, I.J., 2004. Gold tailings as a source of waterborne uranium contamination of streams: Koekemoer Spruit (Klerksdorp gold fields, South Africa). III. Fluctuations of stream chemistry and their impacts on uranium mobility. Water SA 30, 233-239.

Witkowski, E.T.F., Weiersbye, I.M., 1998. Establishment of plants on gold slimes dams: characterization of the slimes and adjacent soils. Plant Ecology and Conservation Series No. 6, AngloGold Ltd, Johannesburg, South Africa.

Wullschleger, S.D., Meinzer, F.C., Vertessy, R.A., 1998. A review of whole-plant water use studies in trees. Tree Physiology 18, 499-512.

Zhang, L., Dawes, W.R., Walker, G.R., 1999. Predicting the effect of vegetation changes on catchment average water balance. CSIRO Technical Report 99/12, CRC for Catchment Hydrology, CSIRO, Canberra, Australia.

Captions to Figures

Figure 1. The location of West Wits and Vaal River trial sites.

Figure 2. The relation between stem diameter at 30 cm above ground level, and the dry mass of leaves, for *S. pendulina* (Crichton, 2010).

Figure 3. Daily whole plot sap flow, ET_0 and rainfall recorded at the Vaal River *S. pendulina* site.

Figure 4. The relation between stem diameter at 30 cm above ground level, and the dry mass of leaves, for *S. lancea* (Crichton, 2010).

Figure 5. Daily whole plot sap flow, ET_0 and rainfall recorded at the West Wits *S. lancea* site.

Table 1. Climate at West Wits (*S. lancea* plot) and Vaal River (*S. pendulina* plot), showing geographical coordinates, altitude, mean annual precipitation (MAP), mean annual reference evaporation (ETo), mean annual temperature (MAT), number of frost days per year and mean annual wind speed (*u*).

District	Latitude	Longitude	Altitude (m.a.s.l.)	MAP (mm)	[1]ETo (mm)	[1]MAT (°C)	[2]Frost days (no. y^{-1})	[3]*u* ($m\ s^{-1}$)
West Wits	26° 25’ 55.18” S	27° 20’ 05.03” E	1 637	704	1 273	15.6	33	[3a]2.94
Vaal River	26° 59’ 20.91” S	26° 46’ 30.83” E	1 320	646	1 330	16.8	34	[3b]2.51

[1]Schulze (1997); [2]Mucina and Rutherford (2006); (3) Mean annual wind speed at Potchefstroom (3a) and Klerksdorp (3b), 2001-2009.

Table 2. Stem diameter, sapwood area, dry leaf mass, specific leaf area and leaf area calculated for *S. pendulina* stems used for sap flow measurements. Measured annual sap flow per stem is also shown.

	Tree 1		Tree 2		Tree 3		Tree 4	
	Stem 1	Stem 2	Stem 3	Stem 4	Stem 5	Stem 6	Stem 7	Stem 8
Stem diameter Mar 2009 (cm)	[a]5.9	5.2	6.0	5.1	6.5	7.5	5.4	6.2
Sapwood area (cm^2)	20.9	16.3	21.1	15.7	24.7	30.9	17.9	22.9
Estimated dry leaf mass (kg)	[b]0.264	0.204	0.273	0.196	0.321	0.428	0.220	0.291
Specific leaf area (m^2 kg^{-1})	[c]8.9							
Estimated leaf area (m^2)	[d]2.345	1.817	2.426	1.747	2.852	3.809	1.961	2.593
Measured sap flow (l y^{-1})	510.3	683.4	1154.4	624.5	754.1	1404.8	325.1	720.1

b=0.0073*a^2.0205; d=b*c

Table 3. Estimation of total sub plot leaf dry mass, leaf area, leaf area index and estimated annual sap flow volumes for the *S. pendulina* plot at Vaal River.

Stem diameter classes (cm)	0.5 – 2.5	2.6 – 4.5	4.6 – 6.5	6.6 – 8.5	8.6 – 10.5
Mid-point (cm)	[a]1.5	3.5	5.5	7.5	9.5
No. of stems in size class used for sap flow measurement	0	0	7	1	0
Dry leaf mass per mean stem (kg)	[b]0.017	0.092	[c]0.229	0.428	0.690
Dry leaf fraction of mean class	[d]0.074	0.402	1	1.869	3.013
Estimated annual sap flow in mean stem (l)	[e]50.4	273.8	[f]681.1	1402.8	2052.1
No. of stems in sub plot falling in each stem size class	[g]26	46	45	30	1
Annual sap flow per stem size class (l)	[h]1310.4	12594.8	30649.5	42084.0	2052.1
Total annual sap flow in sub-plot (mm)			[i]591.3		
Total dry leaf mass in each class (kg)	[j]0.442	4.232	10.305	12.840	0.690
Total leaf area in each class (m^2)	[k]3.934	37.665	91.715	114.276	6.141
Total leaf area in sub plot (m^2)			[l]253.731		
Area of sub plot (m^2)			[m]150		
LAI			[n]1.69		

Sapwood depth = 2 cm; Wood density = 0.5 g cc^{3}; Moisture fraction = 1.16; Wound width = 0.3 cm; SLA= 8.9 m^2 kg^{1}; b=0.0073*a^2.0205; d=b/c; e=d*f; h= mean of probe data or estimated from leaf mass fraction of mean class; i=∑all annual sap flows/m; j=b*g; k=j*SLA; n=l/m

Table 4. Stem diameter, sapwood area, dry leaf mass, specific leaf area and leaf area calculated for *S. lancea* stems used for sap flow measurements. Measured annual sap flow per stem is also shown.

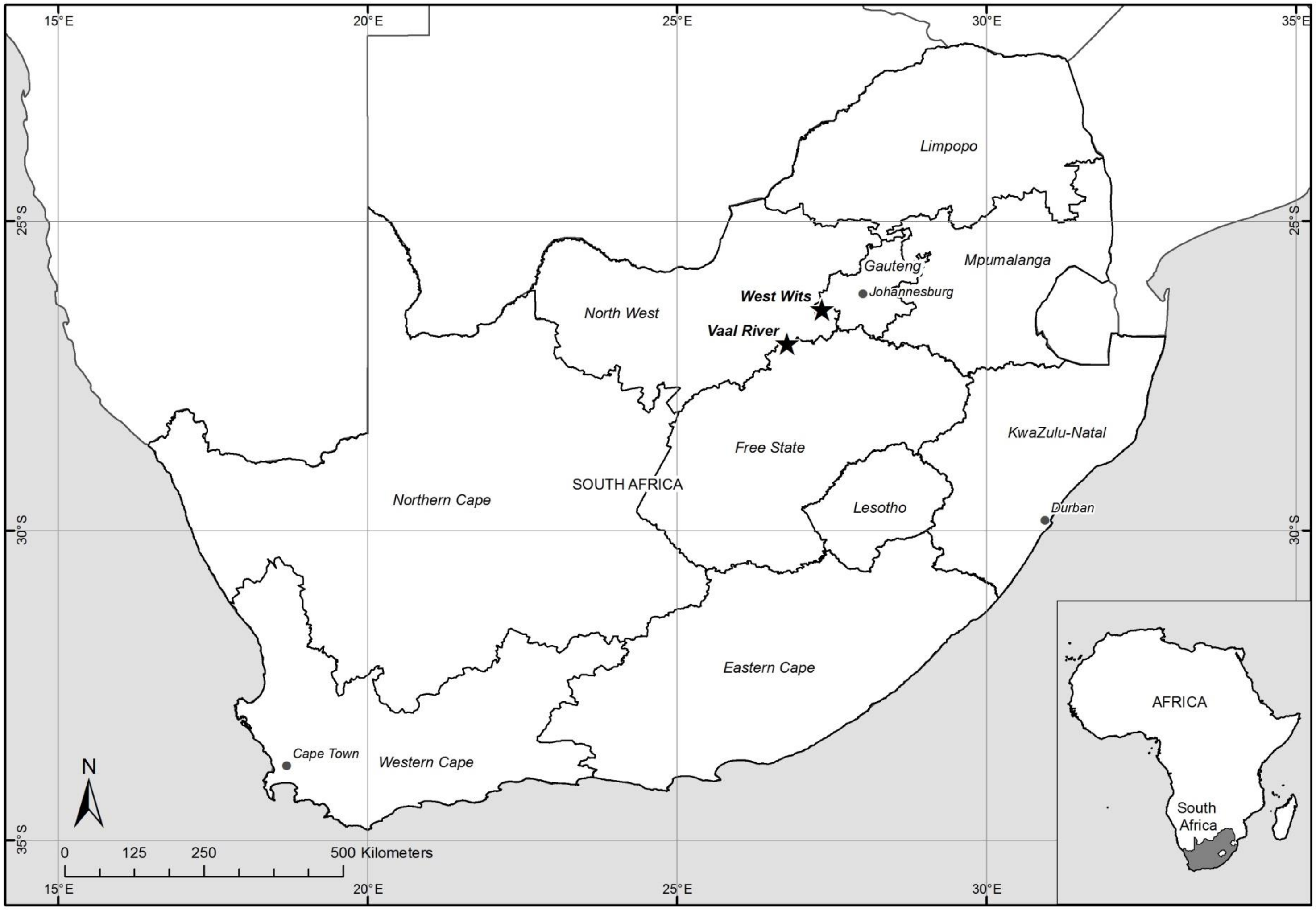
	Tree 1		Tree 2		Tree 3		Tree 4	
	Stem 1	Stem 2	Stem 3	Stem 4	Stem 5	Stem 6	Stem 7	Stem 8
Stem diameter Sep 2009 (cm)	[a]7.6	8.8	5.6		6.8	5.7	5.5	7.8
Sapwood area (cm^2)	31.4	39.0	18.8		26.4	19.5	18.2	32.7
Estimated dry leaf mass (kg)	[b]0.759	1.053	0.384		0.592	0.399	0.369	0.804
Specific leaf area (m^2 kg^{-1})	[c]8.7							
Estimated leaf area (m^2)	[d]6.603	9.160	3.339		5.151	3.474	3.208	6.997
Measured sap flow (l y^{-1})	711.5	3052.5	994.4		1432.2	1212.9	1733.2	1578.4

b = 0.0082*a^2.2325; d=b*c

Table 5. Estimation of total sub plot leaf dry mass, leaf area, leaf area index and estimated annual sap flow volumes for the *S. lancea* plot at West Wits.

Stem diameter classes (cm)	0.5 – 2.5	2.6 – 4.5	4.6 – 6.5	6.6 – 8.5	8.6 – 10.5
Mid-point (cm)	[a]1.5	3.5	5.5	7.5	9.5
No. of stems in size class used for sap flow measurement	0	0	3	3	1
Dry leaf mass per mean tree (kg)	[b]0.020	0.134	[c]0.369	0.737	1.249
Dry leaf fraction of mean class (kg)	[d]0.054	0.363	1	1.997	3.385
Estimated annual sap flow in mean stem (l)	[e]70.9	476.8	[f]1313.5	1240.7	3052.5
No. of stems in sub plot falling in each stem size class	[g]1	8	11	8	1
Annual sap flow per stem size class (l)	[h]70.9	3814.4	14448.5	9925.6	3052.5
Total annual sap flow in sub-plot (mm)			[i]1043.7		
Total dry leaf mass in each class (kg)	[j]0.020	1.075	4.056	5.895	1.249
Total leaf area in each class (m^2)	[k]0.176	9.355	35.285	51.286	10.867
Total leaf area in sub plot (m^2)			[l]106.969		
Area of sub plot (m^2)			[m]30.00		
LAI			[n]3.57		

Sapwood depth = 2 cm; Wood density = 0.65 g cc ^{3}; Moisture fraction = 0.79; Wound width = 0.3 cm. SLA = 8.7 m^2 kg ^{1}; b= 0.0082*a^2.2325; d=b/c; e=d*f; h=mean of probe data or estimated from leaf mass fraction of mean class; i=∑all annual sap flow/m; j=b*g; k=j*SLA; n=l/m


15°E
20°E
25°E
30°E
35°E
25°S
30°S
35°S
Limpopo
Gauteng
Mpumalanga
Johannesburg
West Wits
North West
Vaal River
Free State
KwaZulu-Natal
SOUTH AFRICA
Northern Cape
Lesotho
Durban
Eastern Cape
Cape Town
Western Cape
N
0
125
250
500 Kilometers
AFRICA
South Africa

672 Figure 1

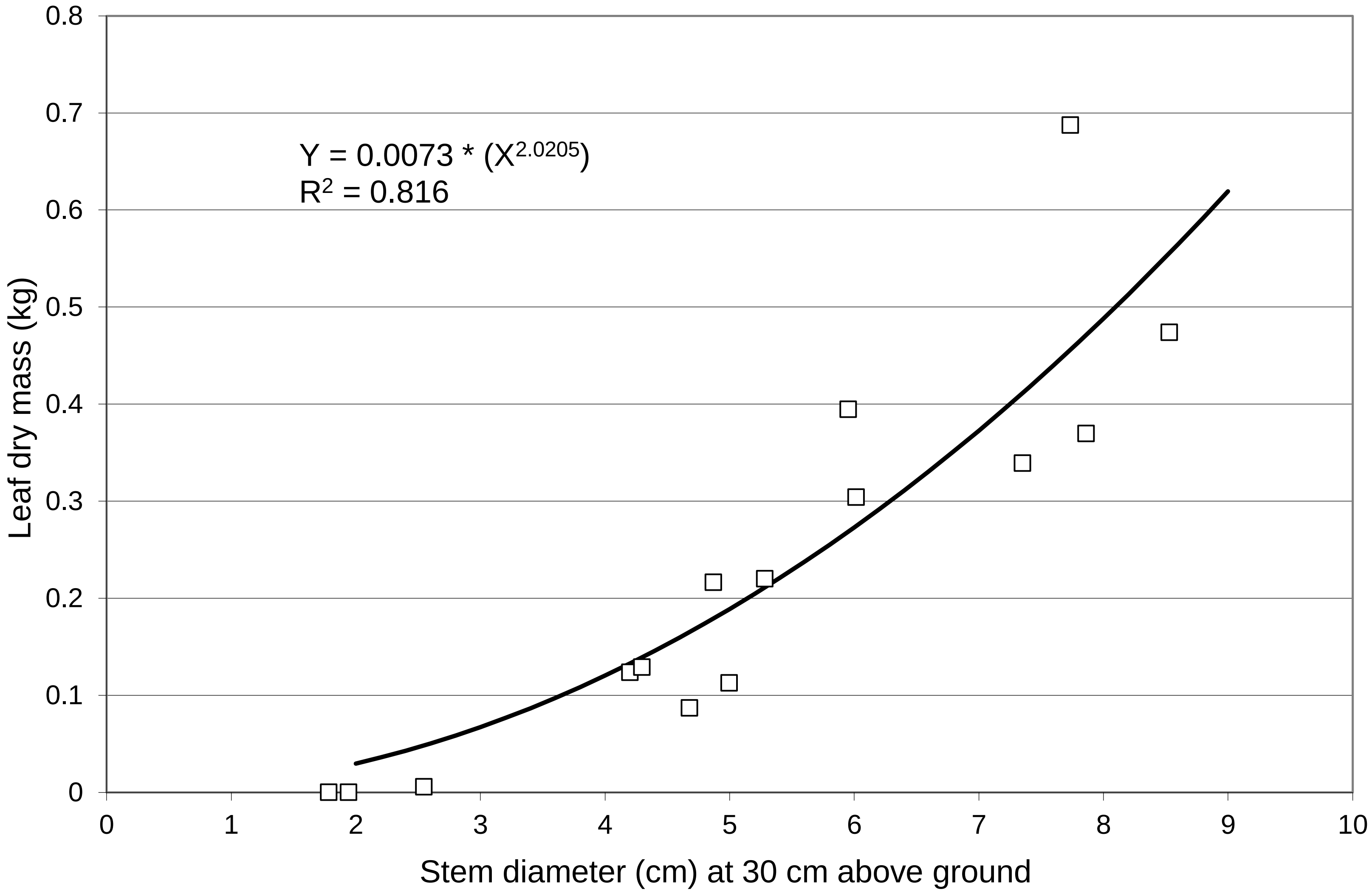

Y = 0.0073 * (X^2.0205)
R² = 0.816
Leaf dry mass (kg)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
1
2
3
4
5
6
7
8
9
10
Stem diameter (cm) at 30 cm above ground

Figure 2

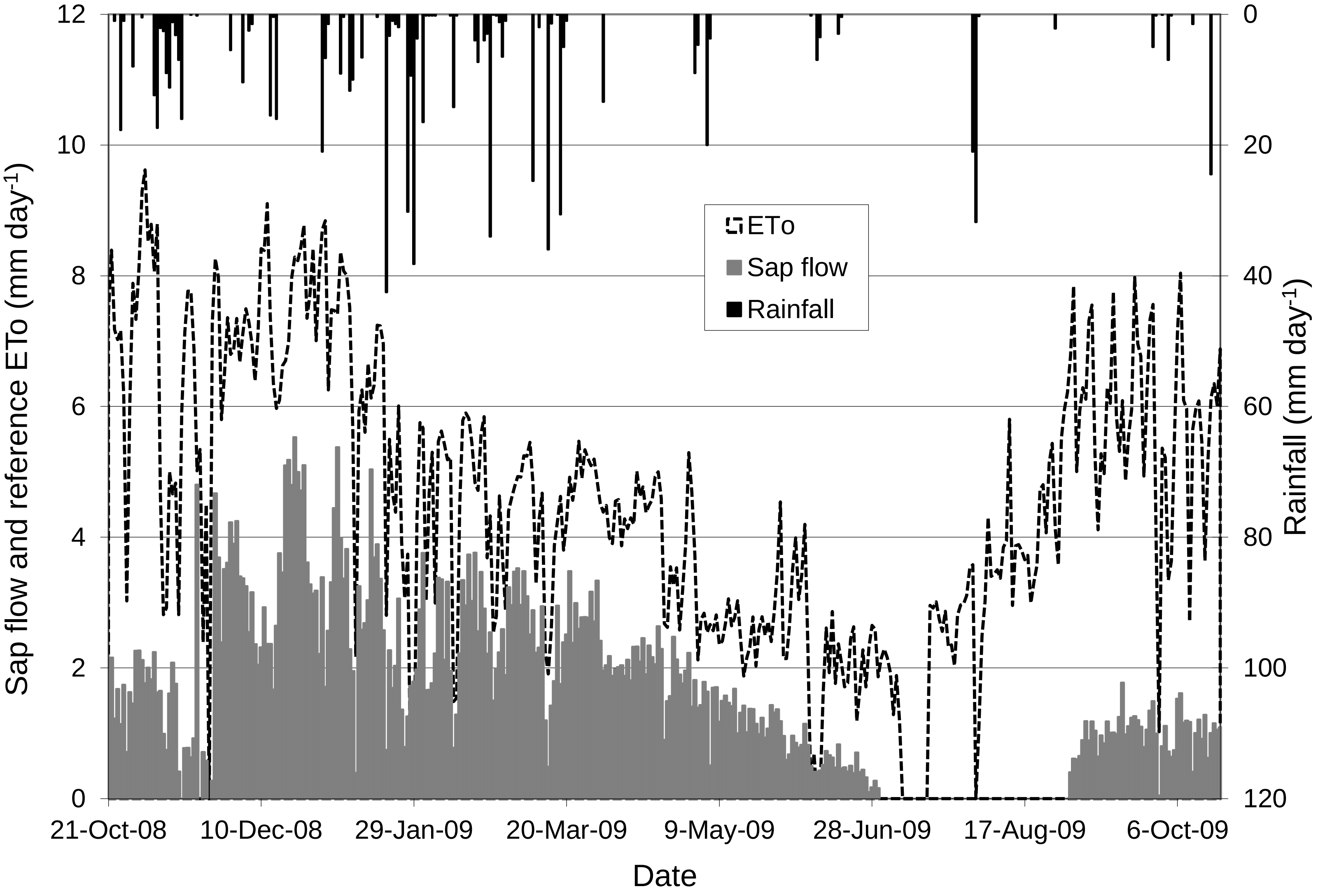
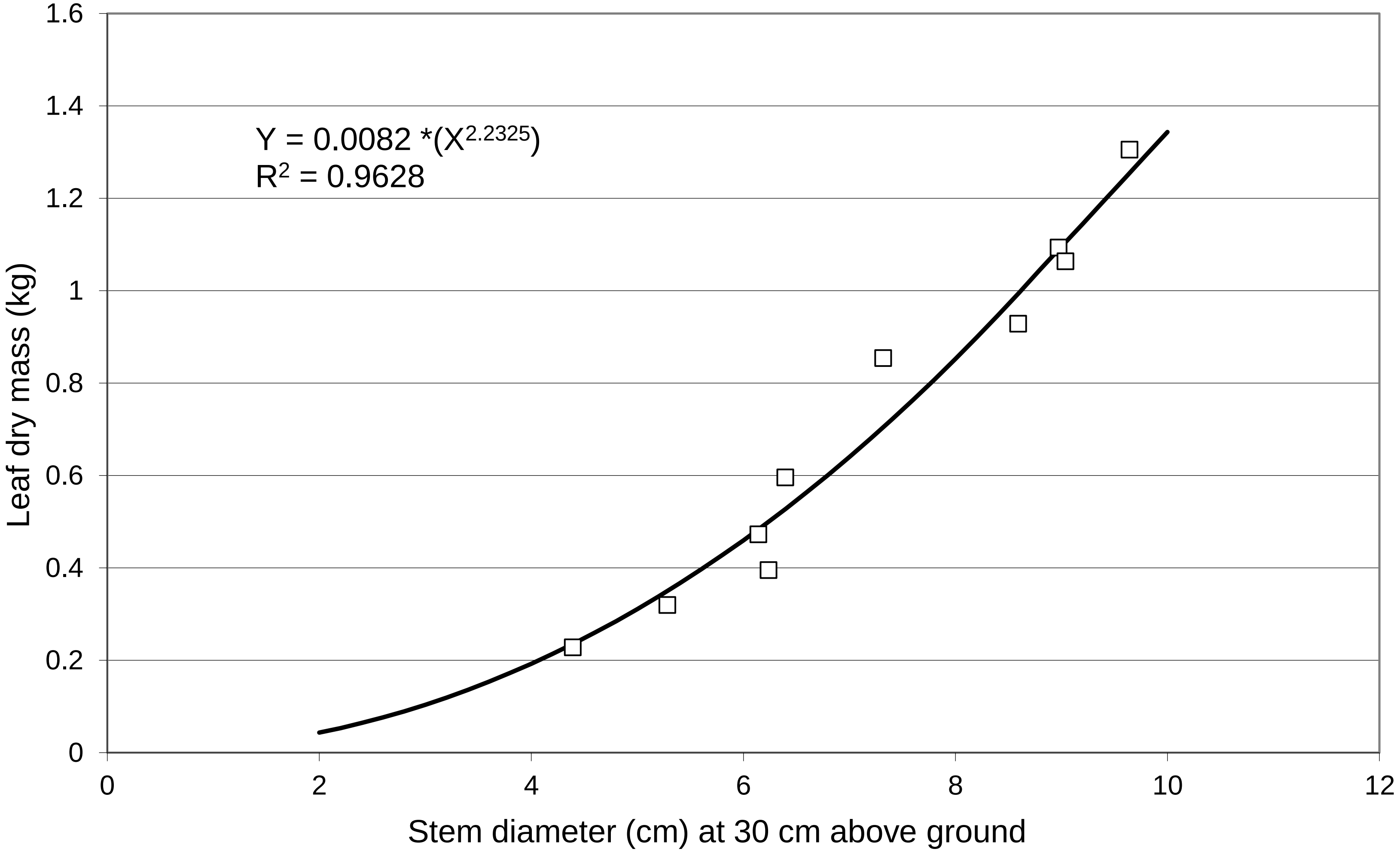
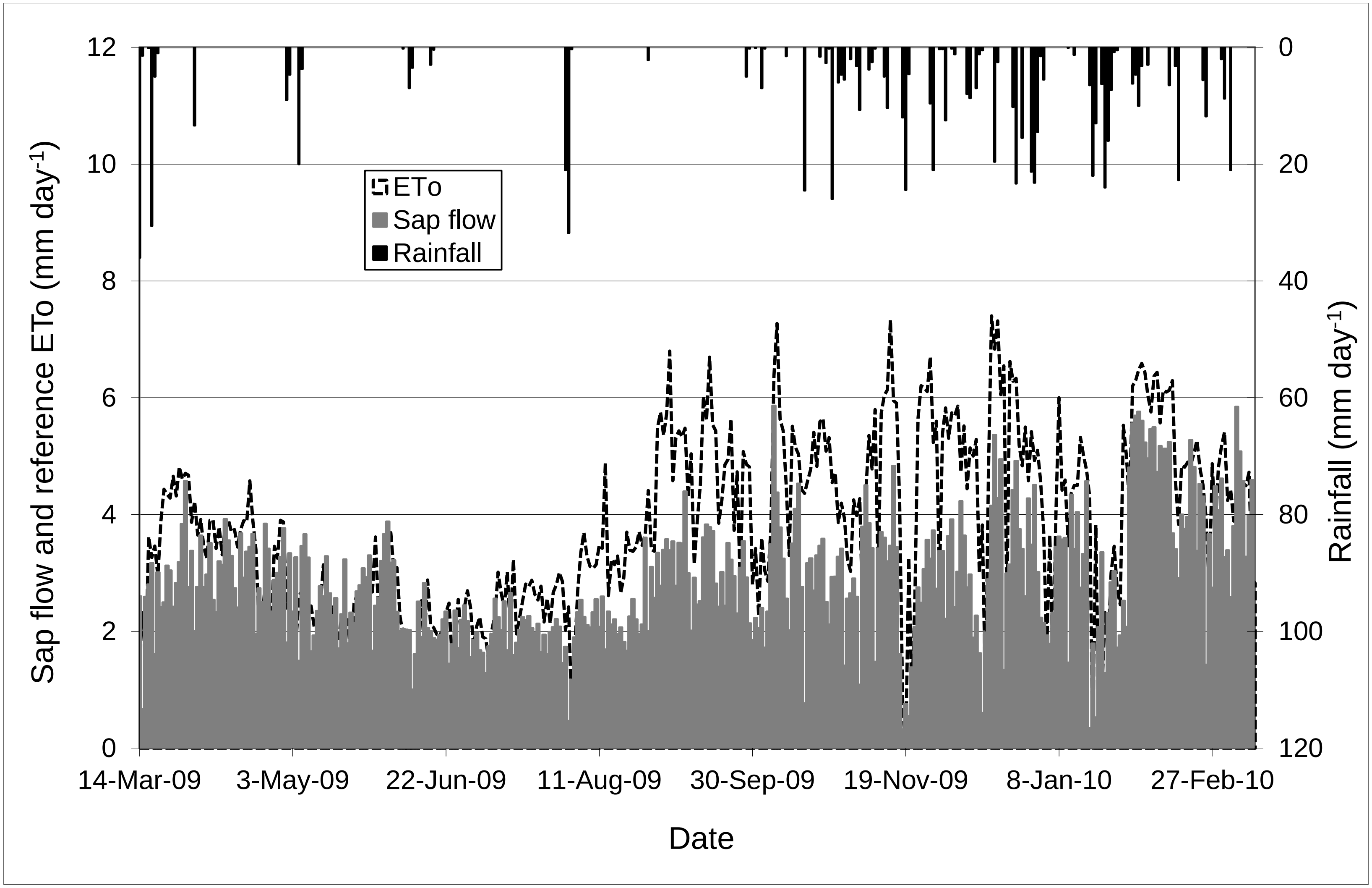

12
10
8
6
4
2
0
0
20
40
60
80
100
120
Sap flow and reference ETo (mm day-1)
Rainfall (mm day-1)
ETo
Sap flow
Rainfall
21-Oct-08
10-Dec-08
29-Jan-09
20-Mar-09
9-May-09
28-Jun-09
17-Aug-09
6-Oct-09
Date

Figure 3



Y = 0.0082 *(X^2.2325)
R² = 0.9628
Leaf dry mass (kg)
Stem diameter (cm) at 30 cm above ground
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
2
4
6
8
10
12

Figure 4



ETo
Sap flow
Rainfall
Sap flow and reference ETo (mm day^{-1})
Rainfall (mm day^{-1})
Date
0
2
4
6
8
10
12
120
100
80
60
40
20
0
14-Mar-09
3-May-09
22-Jun-09
11-Aug-09
30-Sep-09
19-Nov-09
8-Jan-10
27-Feb-10

Figure 5