Comparative water use of wattle thickets and indigenous plant communities at riparian sites in the Western Cape and KwaZulu-Natal

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Abstract

Large-scale funding by both the Government and the private sector continues in support of the Working-for-Water Programme, which is active in many regions of the country. One justification for this programme of alien tree removal is the streamflow enhancement that is believed to follow the replacement of dense stands of invasive trees by indigenous, largely herbaceous or shrub-dominated plant communities. Often the densest stands of invader trees occur within riparian zones, where removal of trees in close proximity to stream channels is believed to strongly enhance streamflow. Few data are available, however, to support this assumption. Results from a number of research catchments have consistently shown that afforestation significantly decreases streamflow where the pre-afforestation vegetation was seasonally dormant mountain grassland or fynbos (Versfeld, 1994). The net difference in evapotranspiration (ET) between riparian thickets of alien trees and riparian fynbos may be quite different, due to the yearlong availability of soil water and enhanced plant growth in riparian zones. The water use of alien invasive trees in South Africa remains largely unknown, adding further uncertainty to the effect of alien removal on streamflow. This paper describes the results of a comparative study of annual ET between indigenous riparian plant communities and riparian wattle thickets (*Acacia mearnsii*) at four sites in the Western Cape and KwaZulu-Natal.

The Bowen ratio energy balance (BREB) technique was used to record a 12-month record of 20 min evaporation rates from a fynbos riparian plant community in the Jonkershoek valley (Western Cape), and a grassland riparian community on the property Gilboa in the KwaZulu-Natal midlands. Closed-canopy, mature stands of self-established *A. mearnsii* in the Wellington and Groot Drakenstein areas of the Western Cape were selected to provide comparative transpiration data. The heat pulse velocity (HPV) technique was used to record hourly sap-flow rates in six sample trees representing the range of tree sizes at both wattle sites. Total daily sap flow in all sample trees experiencing adequate soil water availability was found to be very closely correlated to tree size and an index defined as the product of mean daily vapour pressure deficit (VPD) of the air and the number of daylight hours. These relationships were used to predict the water use of wattle thickets at Jonkershoek and Gilboa, using VPD and day-length data recorded at these sites. Published estimates of canopy rainfall interception were added to the sap flow (transpiration) component to yield a combined annual ET to compare to the BREB ET data. Table 1 summarises the annual evapotranspiration at each site.

TABLE 1
A summary of annual ET differences among the study sites

Locality	Vegetation	Annual evapotranspiration estimate (mm)			
		Transpiration	Rainfall interception	ET	Difference
Jonkershoek	*A. mearnsii* Fynbos	1 318	185	1 503 1 332	171
Gilboa	*A. mearnsii* Grassland	1 077	183	1 260 836	424

We conclude that the removal of riparian wattle and its replacement by indigenous herbaceous plants may indeed result in significant reductions in annual ET, and could very likely lead to streamflow enhancement. However, this study has clearly shown that annual ET varies considerably in different riparian plant communities, and that one must consider the structural and physiological characteristics of both the pre-clearing and post-clearing vegetation in order to predict the net change in ET. This conclusion supports an earlier view (Versfeld et al., 1998) that an improved methodology of general applicability is required to enhance the accuracy of water use predictions for a wide range of alien and indigenous plant communities. Such predictions are important to prioritise clearing operations in areas invaded by alien trees.

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Received 12 January 2001; accepted in revised form 23 July 2001.

Introduction

Several recent developments in South Africa have highlighted the need for better information on the water use of trees in riparian zones. The declaration of plantation forestry as a streamflow reducing activity (SFRA) has served to maintain interest in the issue of forest water use, and the extent to which their impact on catchment water yields may be minimised. One long-recognised option is to remove plantations a set distance away from streams, and to promote indigenous, preferably herbaceous vegetation in its place. The trend towards forest certification has similarly encouraged growers to exclude forestry from riparian zones as a means of minimising the hydrological impacts of their forests on catchment yields, and ensuring the sustainability of their forestry enterprise.

It is, however, the problem of self-established alien invasive trees that has received the most publicity in recent years. Large-scale funding by both the Government and the private sector continues in support of the Working-for-Water Programme, which is active in many regions of the country. An important justification for this programme of alien tree removal is the streamflow enhancement that is believed to follow the replacement of dense stands of invasive trees by indigenous, largely herbaceous or shrub-dominated plant communities. Often the densest stands of invader trees occur within riparian zones, where removal of trees in close proximity to stream channels is believed to strongly enhance streamflow.

Few data are available to quantify these assumptions. Portable weir experiments (Dye and Poulter, 1995; Prinsloo and Scott, 1999) have shown streamflow enhancement immediately following the clearance of riparian trees, but do not take into account water use by the indigenous plant community that in time re-develops on the site. Scott and Lesch (1995) document changes in streamflow following clearance of riparian trees in four research catchments. Their paper illustrates how variable streamflow response can be to this treatment, and how important the characteristics of the post-felling vegetation are in determining hydrological response.

Results from a number of research catchments have consistently shown that catchment-wide afforestation significantly decreases streamflow where the pre-afforestation vegetation was seasonally dormant mountain grassland or fynbos (Versfeld, 1994). The net difference in ET between riparian thickets or plantations of alien trees and indigenous riparian vegetation may be quite different, however, due to the yearlong availability of soil water and enhanced plant growth in riparian zones, and the occurrence of many different types of indigenous riparian vegetation. The water use characteristics of thickets of alien self-established trees in South Africa remain largely unknown, adding further uncertainty to the effect of alien tree removal on streamflow.

This paper describes the results of a comparative study of ET between indigenous riparian plant communities and riparian wattle (*A. mearnsii*) stands, at sites in the Western Cape and KwaZulu-Natal midlands. A recent assessment of the extent of alien invading plants in South Africa listed *A. mearnsii* as the most pervasive species of invader tree in all parts of the country (Versfeld et al., 1998). It is perceived as having a large and negative impact on streamflow and catchment yields, because of its propensity to spread rapidly along riparian zones, quickly forming dense thickets characterised by high biomass and leaf area.

The objectives of the project were to:

- record the annual pattern of ET of *A. mearnsii* growing in dense self-established riparian thickets;
- record the annual pattern of ET of contrasting examples of indigenous riparian plant communities; and
- summarise the annual reduction in ET by riparian vegetation that can be achieved through the removal of exotic invader trees.

Methods

Evaporation measurement techniques

Bowen ratio energy balance (BREB) technique

The two indigenous riparian plant communities selected at Jonkershoek (Western Cape) and Gilboa (KwaZulu-Natal) comprise a complex assemblage of species. The most appropriate and practical technique for measuring evaporation rates was judged to be the BREB method. This technique has been comprehensively described by Savage et al. (1997) and has been extensively deployed in previous experiments in South Africa (e.g. Everson et al., 1998; Burger, 1999). The standard BREB sensors (net radiation, air temperature, air humidity, soil temperature, soil heat flux) were supplemented by either a LI-COR PAR sensor (LI-190SB quantum sensor; LI-COR Inc., Box 4425, Lincoln, Nebraska 68504, USA) or a pyranometer sensor. A Campbell temperature and humidity probe (CS500, Campbell Scientific Inc., 815W. 1800 N. Logan, Utah 84321-1784, USA) was also installed at each site. The BREB arms supporting temperature sensors and air intake nozzles were positioned 1 m apart at both study sites, with the lower arm at a height of 1.3 m above the ground. Measurements of ET were recorded every 20 min over a full year. Volumetric soil water in the top 100 mm of soil was measured at fortnightly intervals from three sample cores removed from the vicinity of the BREB systems. Analysis of data was accomplished using a custom-developed Visual Basic Program (BOWCALC).

Heat pulse velocity technique

Sap flows within trees in the two wattle stands (Wellington and Groot Drakenstein, Western Cape) were measured using the heat pulse velocity (HPV) technique, which has previously been shown by Smith et al. (1992) to provide valid estimates of sap flow in *A. mearnsii*. The theory, instrumentation specifications and field procedure pertaining to this technique have been described in great detail in several previous publications (Olbrich, 1991; Dye and Olbrich, 1992; Dye, 1996) and so are not repeated here.

The following sap-flow data analysis procedure was adopted. The raw data were first examined using a custom-developed Visual Basic Analysis Program to identify probes with missing or faulty data, those with long null-balance times, and those exhibiting poor correlation with other probe sets. Missing data were patched using data from another probe set with which it was most highly correlated. Long null-balance times that indicate slow sap-flow rates were sometimes recorded by the deepest probes, indicating close proximity to heartwood. These probes were excluded where the number of missing data was high. Patched files were saved and subsequently read again during the calculation of sap flow. The analysis programme calculated hourly sap flow for the tree, and then saved the output in three files containing the hourly sap-flow rates, daily total sap flow, and the parameters used in the calculations. The daily data files were concatenated using a text editor. Partial days at the start and end of files were joined appropriately, and the complete data record was converted to an Excel file. These files were then checked as follows:

- The whole-year pattern was examined to check for unusually high and low values, and marked discontinuities.
- Readings taken at times when transpiration rates were not reduced by soil water deficits were plotted against mean daily VPD. High non-linear correlations are typical under these conditions, and suspect data are immediately apparent.

Where suspect data were identified, they were removed and replaced with patched data based on the mean daily sap flow for 10 d periods immediately before and after the period in question. Wound sizes could not be discerned in excised wood samples, due to discoloration of the wood by the resin. On the basis of results reported by Smith et al. (1992), it was assumed to be 3 mm in all sample trees.

Site descriptions and sampling procedures

Jonkershoek

Yearlong evaporation was measured at a fynbos riparian site in the upper reaches of the Jonkershoek Valley (Stellenbosch district, 33° 59.336′ S; 18° 57.651′ E). The site lies at an altitude of 325 m a.m.s.l, and mean annual precipitation is 1 324 mm. A BREB system was set up at a location close to the Eerste River where the instruments were surrounded by riparian vegetation. The wind fetch over this vegetation exceeded 100 m both up and down the valley in the prevalent wind directions. Dominant plant species included *Pteridium aquilinum*, *Elegia capensis*, *Cannomois virgata* and *Ischyrolepis gaudichaudiana*. Projected canopy cover of the plant community was approximately 95%, with a mean plant height of 0.5 to 0.75 m. Good quality data were collected from August 1998 to July 1999. Maintenance visits occurred fortnightly.

The geology can be described as quaternary alluvium derived from a mix of the Table Mountain sandstones and Cape Granite of the higher slopes. There is a considerable depth of alluvial material that is sandy and organic, overlying a basement of large, rounded river rocks and stones. The soil profile is between 0.8 m and 1.5 m deep with very few rocks and stones in the upper half. Soil forming is dominated by the accumulation of the organic material as a result of high water levels over much of the year. However, there were no signs of permanent wetness in the upper 1 m of soil. Organic material is fairly well broken down and the profile is black. The soils are of the Rietfontein family of the Champagne form (Ch2200; Soil Classification Working Group, 1991) with a mineral fraction of a coarse sand.

Gilboa

This site was situated on the property Gilboa (owned by Mondi Forests), which lies at the top of the Karkloof hills north of Howick in the KwaZulu-Natal midlands. The altitude of the site is 1 532 m a.m.s.l., and mean annual precipitation is 867 mm. The BREB system was erected near the centre of the Inyamvubu Vlei (30° 15′ E; 29° 15′ S). This vlei is flat and extensive, providing a wind fetch in excess of 150 m in all directions. The soil surface remained wet throughout the summer, with occasional shallow inundation after heavy rainfall, but it dries out during the winter months. The predominant plant species in the vicinity were *Andropogon appendiculatus*, *Helictotrichon turgidulum*, *Tristachya leucothrix*, *Harpechloa falx*, *Helichrysum aureonitens* and *Aristida congesta*. The system was operational from early spring of 1998/99. Because of persistent technical problems during this summer, monitoring was extended into the 1999/2000 growing season. Maintenance visits occurred every 2 to 3 weeks.

Wellington

A closed-canopy, mature, self-established riparian wattle thicket was located on the farm Oaklands (33° 26.084’ S; 19° 04.892’ E), which lies northeast of Wellington, and east and south of the Groenberg, a free-standing mountain of the Malmesbury Shale Formation. Mean annual rainfall in the area is 1 050 mm, and the altitude is 345 m a.m.s.l (Prinsloo and Scott, 1999). Locally, the soils are derived from the decomposition of massive sub-greywacke. The soils of the valley bottom are a complex of surface deposits of very coarse alluvial gravels, deposited in lenses of variable size and thicknesses of up to 1m, on deeply weathered and much finer grained *in situ* shales. Where no recent gravels have been deposited, the soil is a well-drained deep Clovelly (Brereton family, Cv1200 clay loam) of at least 2 m depth. Below the yellow subsoil there is a further 1 m or more of deeply weathered parent material. Despite its position in the drainage line, the soil at this site displayed no signs of permanent wetness. The recent alluvial deposits are comprised mainly of stones with mean diameters in excess of 20 mm (probably in excess of 80% by volume), and the remainder is a mixture of coarse sand and finer gravel. Apart from the recent gravel lenses, which are all surface deposits of up to 1 m in depth, there are remarkably few rocks in the profile (<5% by volume).

The entire farm was infested with *A. mearnsii*, with particularly dense stands along the riparian zones. Following a survey of tree diameters in a sample plot of 301 m², six sample trees were selected to represent each of six diameter classes of trees (see Table 2). HPV probes were implanted into each sample tree to record sap flux

TABLE 2
A summary of the six diameter size classes defined from an enumeration of all trees within a plot of 301 m² at the Wellington site. The diameter of sample trees chosen to represent each size class, the number of trees within each size class, and the number of HPV probe sets per sample tree are also shown.

	Size class					
	1	2	3	4	5	6
Diameter range (mm)	21 - 50	51 - 100	101 - 150	151 - 200	201 - 250	251 - 300
Diameter of sample tree (mm)	29	55	127	145	210	274
No. of trees in size class	50	34	25	15	9	4
No. of heat pulse probe sets	2	4	4	4	4	6

TABLE 3
A summary of the six diameter size classes defined from an enumeration of all trees within a plot of 300 m^2 at the Groot Drakenstein site. The diameter of sample trees chosen to represent each size class, the number of trees within each size class, and the number of HPV probe sets per sample tree are also shown.

	Size class					
	1	2	3	4	5	6
Diameter range (mm)	0 - 40	41 - 80	81 - 120	121 - 160	161 - 200	201 - 240
Diameter of sample tree (mm)	38	62	114	122	177	223
No. of trees in size class	8	62	28	11	8	4
No. of heat pulse probe sets	2	4	4	4	4	6

densities at depths of 4, 9, 15 and 23 mm beneath the cambium. In the smallest size class, only two probe sets were implanted to depths of 4 and 9 mm beneath the cambium. The largest tree received six probe sets, with additional probes at 26 and 34 mm.

Hourly HPVs were recorded over a period of seven months, starting in August 1997 and ending prematurely in February 1998 when the trees were destroyed by a wildfire. Measurements of sapwood area, sapwood moisture fraction and density, and probe separation distances were used to convert HPVs to whole-tree sap flow. Wound widths were assumed to be 3 mm (Smith et al., 1992), since resin staining around the drilled holes in this long-term study obscured the transition between functional and non-functional sapwood. An automatic weather station was sited approximately 50 m from the sample trees on a grassland hillslope. Hourly means of temperature and relative humidity were recorded over the entire study period, and used to calculate hourly vapour pressure deficit (VPD). Periodic spot measurements of relative humidity were taken with a sling psychrometer to check for possible drift in the response of the Coreci capacitance chip to relative humidity. The sapwood moisture fraction of nearby trees was measured at monthly intervals.

Groot Drakenstein

Since only seven months of data were collected at the Wellington site, it was decided to conduct a further study at another Western Cape riparian wattle site. A new site was chosen on the slopes of the Groot Drakenstein mountains (33^o 54.595’ S; 18^o 58.530’ E) in the vicinity of Pniel, close to Stellenbosch. This site lies at an altitude of 275 m and is situated toward the upper side of a broad, evenly sloping footslope below the craggy Groot Drakenstein Mountains. Mean annual precipitation was estimated at 906 mm. Wattle infestation in the area was severe, but was in the process of being cleared by Working-for-Water teams. The mountains are composed of quartzitic Table Mountain Sandstones and the adjacent slope is quaternary scree and piedmont and terrace gravels of the same sandstone source. The streams draining the high rainfall mountains split into many smaller and poorly defined drainage channels when they reach the gently sloping footslope. Much drainage is expected to be underground.

A riparian study site was selected adjacent to a watercourse associated with dense *A. mearnsii* trees that were substantially taller than those in the surrounding area. Soils are of the Waterton family of Fernwood form (Fw2110) with coarse sands and a high rock and gravel content. Soils are especially variable spatially because of the complex of alluvial and colluvial sources of deposits. Occasional organic profiles are possible along the drainage lines, but generally the soils are too shallow, warm and dry for higher organic matter development. The soil indicates that the primary soil-forming mechanism is elluviation of the seasonally saturated subsoil, which is a pale to medium grey colour and underlain by coarse gravels and rock of mixed alluvial and colluvial origin. The mineral soil fraction is coarse and very coarse, and the profiles are freely draining above the E-horizon.

A survey of tree diameters was performed in a plot measuring 30 by 10 m, orientated along the channel and including both banks of the channel. On the basis of 121 measurements, six size classes were defined (Table 3). Six sample trees representing each of these size classes were chosen for heat pulse monitoring. HPV probes were again implanted into each sample tree to record sap-flux densities at depths of 4, 9, 15 and 23 mm beneath the cambium. In the smallest size class, only two probe sets were implanted to depths of 4 and 9 mm beneath the cambium. The largest tree received six probe sets, with additional probes at 26 and 34 mm.

A weather station was maintained at an exposed fynbos site within 100 m of the sample trees. VPD was calculated from hourly temperature and relative humidity readings. The latter were checked against spot readings of RH taken with a sling psychrometer at each visit. At the start of the monitoring period, water was flowing strongly in the channel, but flow ceased by January. The site was burnt out by wildfire in March 1999 after seven months of sap-flow record.

Results

Jonkershoek

Figure 1 shows the pattern of daily ET measured through the year, expressed in units of mm equivalent depth of water. Gaps in the data record were caused primarily by problems with the BREB Dew10 humidity sensor. Figure 2 shows the correlation between total daily ET and total daily solar radiation (estimated from the quantum sensor data assuming a conversion factor of 2 200 μmol m$^{-2}\cdot$s^{-1} to 1 000 W$\cdot$m^{-2} (Landsberg and Gower, 1997). The correlation was judged to be sufficiently good to patch the missing days. Greater scatter is evident below than above the fitted line, and is attributed to reduced evaporation caused by high humidity. The cumulative annual ET calculated from the complete patched data set was 1 332 mm.

Gilboa

Figure 3 shows the available data collected from this site from September 1998 until September 1999. Persistent problems with the Dew10 humidity sensor were experienced in November, December and March. This was compounded by logger malfunction caused by a nearby lightning strike in January. Gaps in the data record were too long to patch on the basis of average ET rates immediately before and after the gap. A suitable model was required for this purpose.

The relation between daily solar radiation (SR; MJ $m^{-2} \cdot d^{-1}$) and measured daily ET (mm) was first investigated for all days for which measured ET data were available. Figure 4 shows that a large scatter in data points exists in this relation. High correlation to SR is shown by the ET data collected in March and April (closed symbols), when the plants were fully developed and still physiologically active. The remaining points which mostly fall below this maximum rate of ET indicate times of the year when ET is restricted by low green leaf area, either early (Sep) or late (Jun to Aug) in the growing season. The theoretical annual trend in maximum ET was calculated using the relation between SR and peak season ET. Actual ET was then expressed as a fraction of the maximum ET, to derive an empirical seasonal trend (Fig. 5). This is believed to track changing green-leaf area through the season. The first two months of the 1999/2000 season were added to the start of the 1998/99 data, to obtain a pattern of ET over a complete growing season. This pattern shows a steep increase in early spring as the green-leaf area increases rapidly with rising temperature and spring rains. This increase continues at a reduced rate through the summer, reaching a peak in March/April. With autumn senescence, ET drops sharply to very low rates that continue through the winter. Figure 6 shows simulated ET over the complete growing season. Two significant gaps caused by an absence of SR data were patched by ET estimates based on the mean of 10 readings on either side of the gap. Simulation results were judged to be realistic on the basis of the following observations:

- The total ET amounted to 836 mm. This is somewhat greater than the four-year mean of 696 mm (ranging from 651 to 752 mm) recorded by Everson et al. (1998) for high altitude grasslands at Cathedral Peak. The difference is attributed to the lower altitude and higher temperatures at Gilboa, and greater opportunity for soil evaporation from the periodically saturated soil surface. Research catchment data show annual ET of control catchments to range from 700 to 1 000 mm (Bosch and Von Gadow, 1990).
- The single well-defined mid-season peak, as well as the steep increase and decrease at the start and end of the growing season, respectively, closely resemble the pattern of ET recorded at Cathedral Peak (Everson et al., 1998).
- Peak daily ET rates in mid-summer reached 6 mm, which is realistic for grasslands at times of peak physiological activity (Everson et al., 1998).

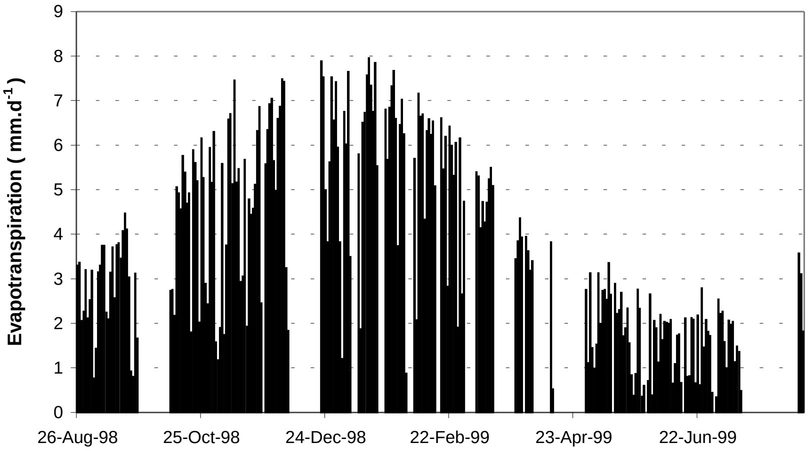

Figure 1
The annual trend in daily ET recorded at the Jonkershoek site

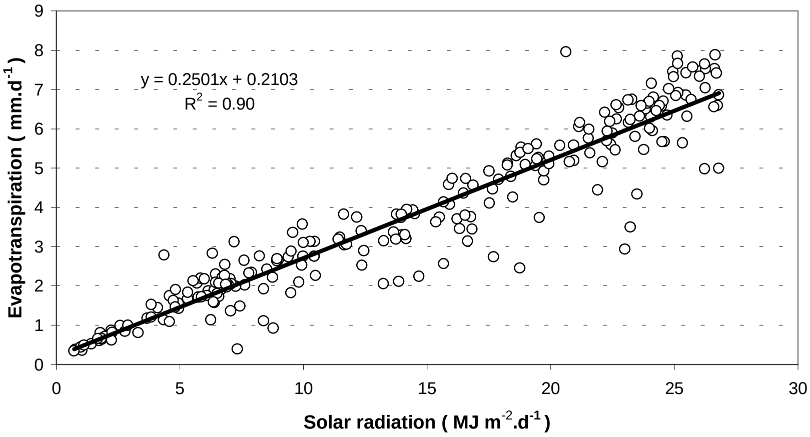

Figure 2
The relation between total daily solar radiation and total daily ET recorded at the Jonkershoek site

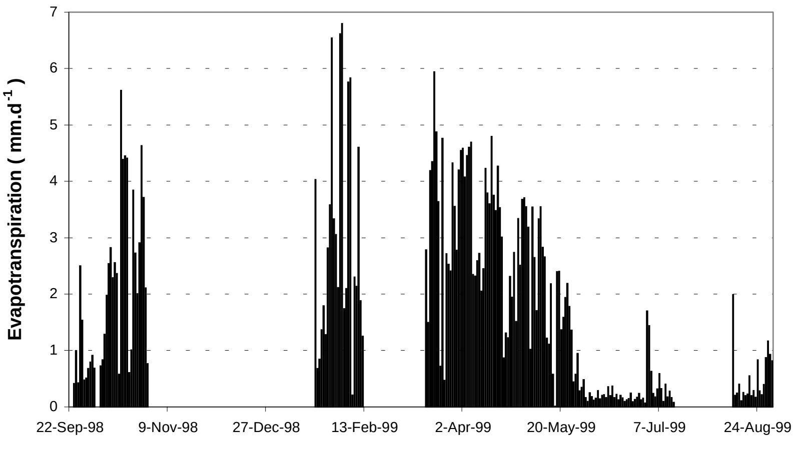

Figure 3
Daily ET data recorded at the Gilboa site

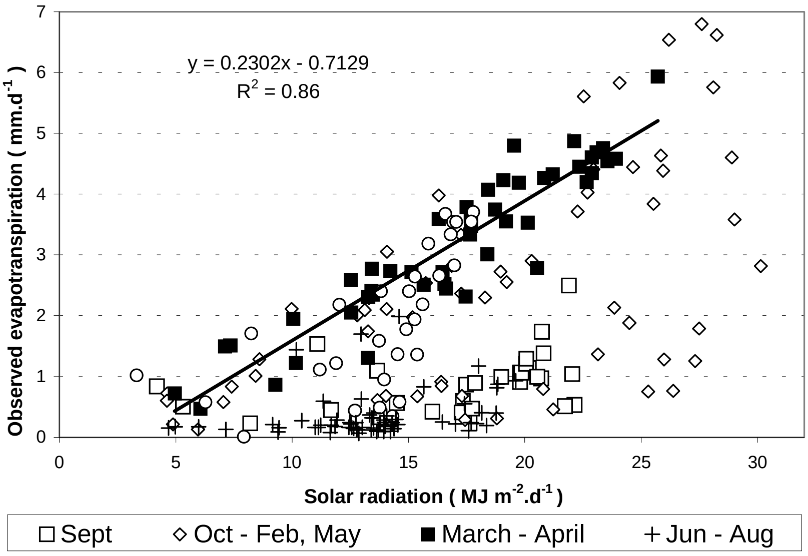

Figure 4
The relation between daily solar radiation and measured daily ET for different periods of the year

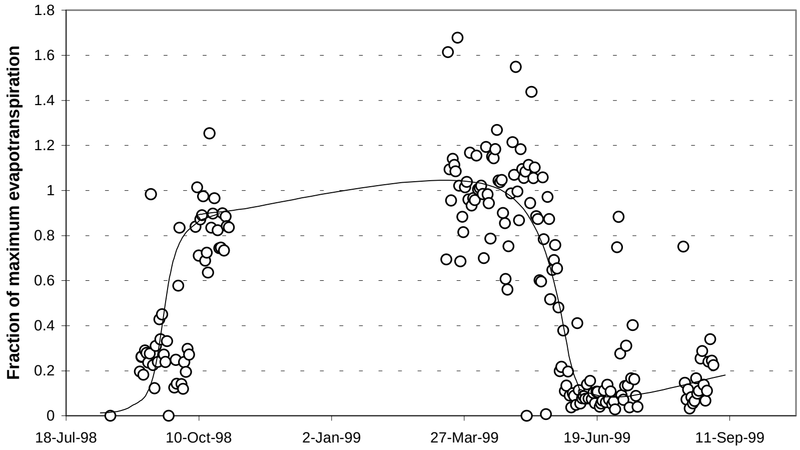

Figure 5
The trend in fraction of maximum daily ET fitted to available data recorded at the Gilboa site

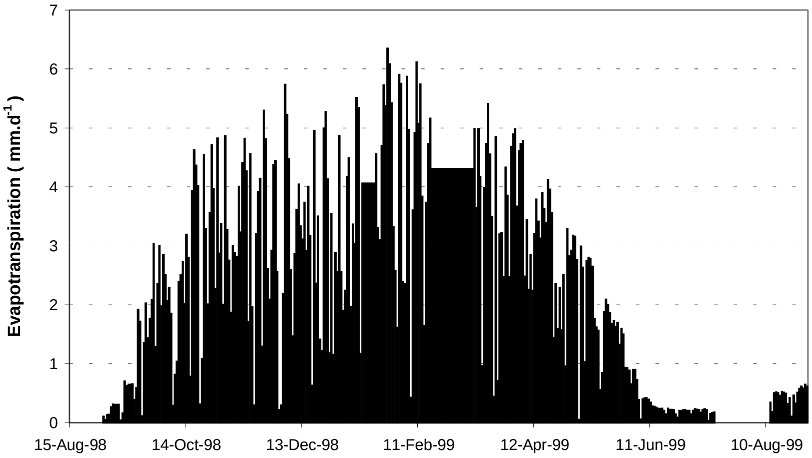

Figure 6
The annual pattern of ET modelled at the Gilboa site. Two periods of constant ET contain patched data based on mean daily ET on either side of the data gap.

Wellington

Figure 7 shows the days when good quality HPV data were recorded from all six sample trees. These data display a typical seasonal pattern of daily ET, with highest values in mid-summer due to long day lengths and high temperatures and VPD. The data suggest periodic incursions of cold and humid air, followed by extended periods of recovery to high sap-flow rates. Daily sap flow in every sample tree was found to be closely correlated to the product of mean daily VPD and the number of daylight hours (Fig. 8). Daylight hours were calculated from the number of hours where solar radiation exceeded zero, the sensor exhibiting a slightly negative offset. Daily plot evaporation was calculated by scaling the sample tree sap flows by the number of trees in the diameter class, and summing across all diameter class totals. Whole-plot sap flow was closely correlated to the product of mean VPD and the number of daylight hours (Fig. 9). No seasonal differences could be discerned in this scatter plot, implying that the trees had access to adequate soil water throughout the monitoring period, which included extremely hot and dry late-summer weather. The sapwood moisture fraction showed no seasonal trend, averaging 0.91 over the monitoring period. We concluded that the relationship shown in Fig. 9 could be used to infer whole-year wattle water use on the basis of the VPD data recorded at Jonkershoek and Gilboa.

Groot Drakenstein

Good quality sap-flow measurements were recorded from August 1998 to February 1999. For each sample tree, total daily sap flow was scaled up by the number of trees of the same size category in the plot. Figure 10 illustrates the trend in whole-plot sap flow over the monitoring period. There is a distinct trend of declining daily sap flow from December onwards, which is not linked to day-length changes, and is attributed to the depletion by the trees of a limited store of soil water. The stream had stopped flowing by January 1999, and the trees were visibly wilting by February. The trend of sapwood moisture fraction also showed a decline from December onward (Fig.11).

Daily sap flow for each of the six sample trees was examined up to the end of November (Fig.12), before stress became evident in the trees. These were again highly correlated to the product of VPD and number of daylight hours, exhibiting very similar trends to those recorded at the Wellington site. Whole-plot daily sap flow was calculated by scaling up each sample tree daily sap flow by the number of trees in the size class it represents. The relation between whole-plot daily sap flow and the mean daily VPD times number of daylight hours, for the period up to the end of November, is shown in Fig.13.

The study was again prematurely terminated by a wildfire. This time, the annual sap flow could not be estimated, since the assumption of non-limiting soil water availability could not be made at this site. Water availability and sap flow could not be forecast with reasonable accuracy over the remaining six months to describe annual water use. The study was valuable in confirming the validity of results recorded at the Wellington site, as well as clearly illustrating that annual water use of vegetation at a site may be significantly reduced by periods of soil water deficits, even in apparently riparian conditions.

Comparison of annual ET among the sites

The annual sap flow in the *A. mearnsii* stands could not be compared directly to annual ET recorded at the Jonkershoek and Gilboa sites for the following reasons:

- Weather conditions at the wattle sites were different to those at the indigenous sites because of differences in geographical location and sample periods.
- The wattle stand measurements did not span a full year.
- The BREB technique records total ET, whereas sap-flow measurements in the wattle stands reflect transpiration rates, but not the canopy interception loss component of ET.

The strategy adopted was to use VPD and day-length data recorded at Jonkershoek and Gilboa to estimate what the daily sap flow of a stand of wattle trees would be at these sites, using the relationship shown in Fig. 9. This assumes that the tree density and size distribution of the Wellington stand is typical of a mature stand that could develop at these sites. The annual sap flow calculated in this way for the Jonkershoek site amounted to 1 318 mm.

Hourly temperature and relative humidity data over a full year were available from a Hobo sensor located within 2 km of the Gilboa site, and these data were used to calculate hourly, and then mean daily VPD. Day length was calculated from the day of year and the site latitude using a formula described by Jones (1983). The product of mean daily VPD and number of daylight hours was then used to predict wattle sap flow under Gilboa climatic conditions. We again assumed the same size distribution and density of trees as was recorded at Wellington. This analysis led to an annual sap-flow estimate of 1 077 mm.

To arrive at an estimate of ET for wattle stands at Jonkershoek and Gilboa (required for comparison with the BREB measurements above

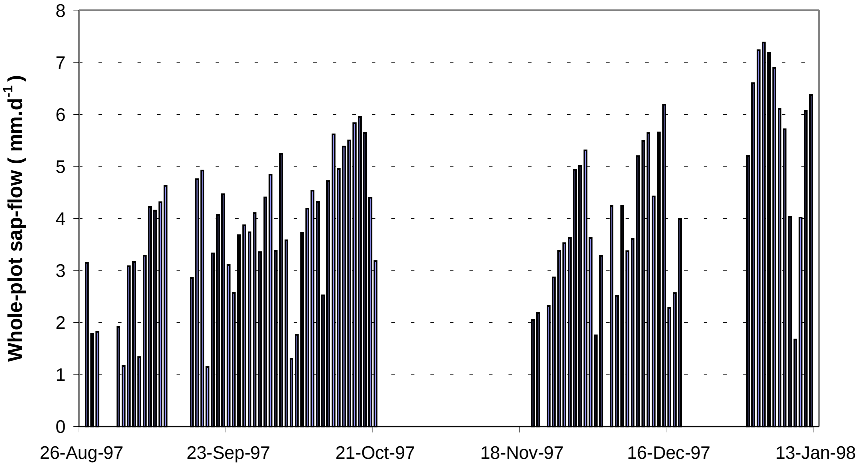

Figure 7
Daily whole-plot sap flow recorded at the Wellington A. mearnsii *site*

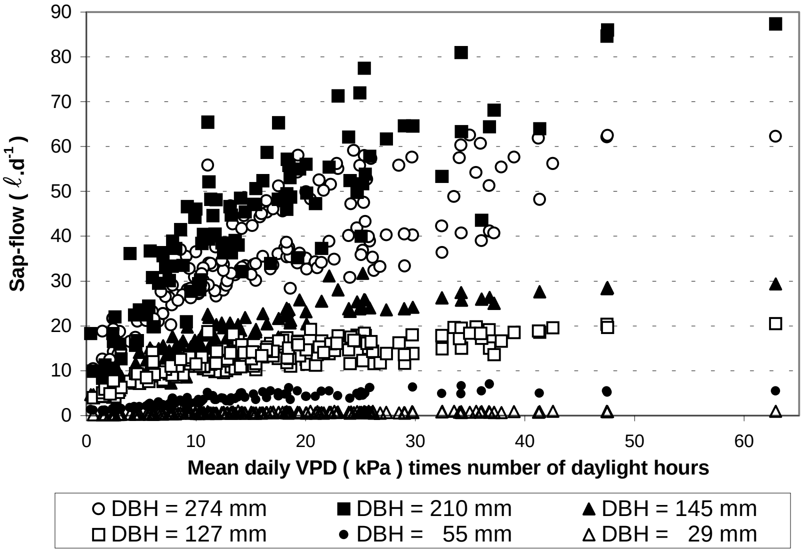

Figure 8
The relation between daily sap flow and the product of mean daily VPD and the number of daylight hours, recorded in six sample trees at the Wellington A. mearnsii *site*

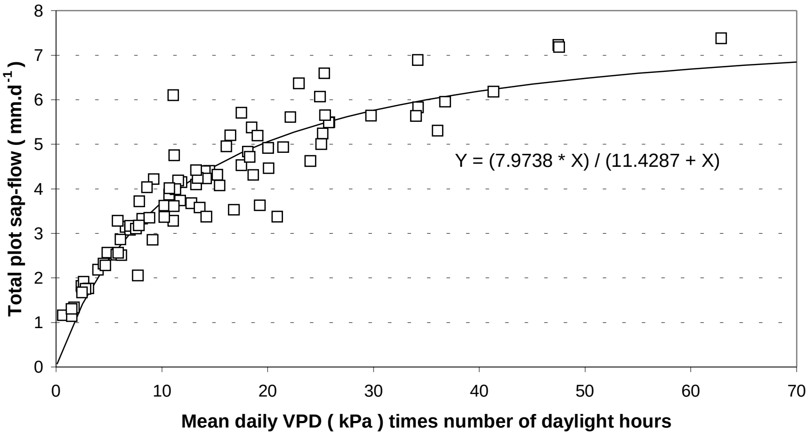

Figure 9
The relation between whole-plot sap flow and the product of mean daily VPD and the number of daylight hours, recorded at the Wellington A. mearnsii *site*

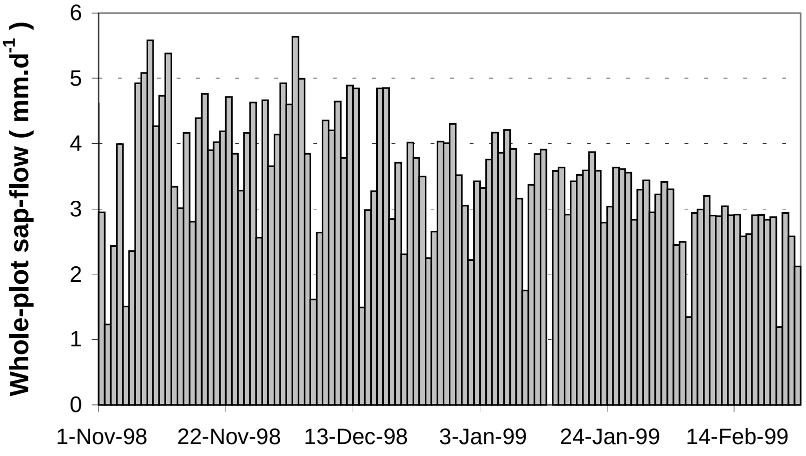

Figure 10
Daily whole-plot sap flow recorded at the Groot Drakenstein A. mearnsii *site*

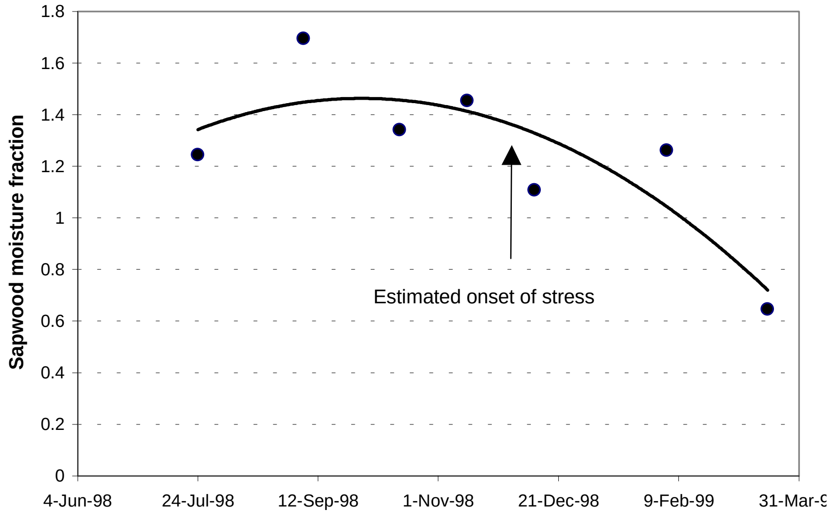

Figure 11
The trend in sapwood moisture fraction recorded at the Groot Drakenstein A. mearnsii *site*

TABLE 4
A summary of annual ET differences among the study sites

Locality	Vegetation	Annual evapotranspiration estimate (mm)			
		Transpiration	Rainfall interception	ET	Difference
Jonkershoek	*A. mearnsii* Fynbos	1 318	185	1 503 1 332	171
Gilboa	*A. mearnsii* Grassland	1 077	183	1 260 836	424

fynbos and grassland), the evaporation of water intercepted on the surfaces of leaves, branches and trunk had to be added to the transpiration (sap flow) component. In the absence of any experimental data for wattle, this component was estimated using a table of daily interception losses provided for this species by Schulze et al. (1995; Table 20.5.5, key 24). Total interception loss was calculated on the basis of these daily losses and the number of sample period rain days recorded at a gauge situated close to the Jonkershoek and Gilboa sites. Where daily rainfall was less than the predicted daily interception loss, it was assumed that the interception loss equalled the daily rainfall. The estimated annual interception loss of 185 mm for the Jonkershoek site (15% of the rainfall total of 1 212 mm) was added to the sap-flow total to yield an estimated annual ET of 1 503 mm. The estimated annual interception loss of 183 mm at Gilboa (17% of the rainfall total of 1 042 mm) was added to the sap flow total to yield an estimated annual ET of 1 260 mm. A summary of annual ET at the four sites is shown in Table 4.

Discussion and conclusions

In a list of research recommendations for enhancing our understanding of the impacts of alien invading plants, Versfeld et al. (1998) cited the need for improved measurement of ET by invading species, especially by *A. mearnsii*. This study has made a useful contribution in this direction, by providing comparative annual ET estimates between riparian wattle stands and indigenous plant communities in two different regions of the country, and by illustrating the major controls on plant ET, and how this may be modelled in other localities.

Comparison of the Jonkershoek and Wellington sites predicts a net decline in annual ET of 171 mm if dense, mature wattle thickets growing in the upper Jonkershoek valley were to be removed and replaced in time by a well-developed riparian fynbos plant community. Likewise, a similar conversion of riparian wattle thicket to grassland at Gilboa would reduce annual ET by 424 mm. It is important to bear in mind that some uncertainty exists over the estimates of canopy interception loss in wattle stands. Figures used in this study are based on relative differences in LAI among different forest stands, and not on actual rainfall interception measurements (Schulze et al., 1995). The rainfall interception losses in wattle stands require experimental investigation.

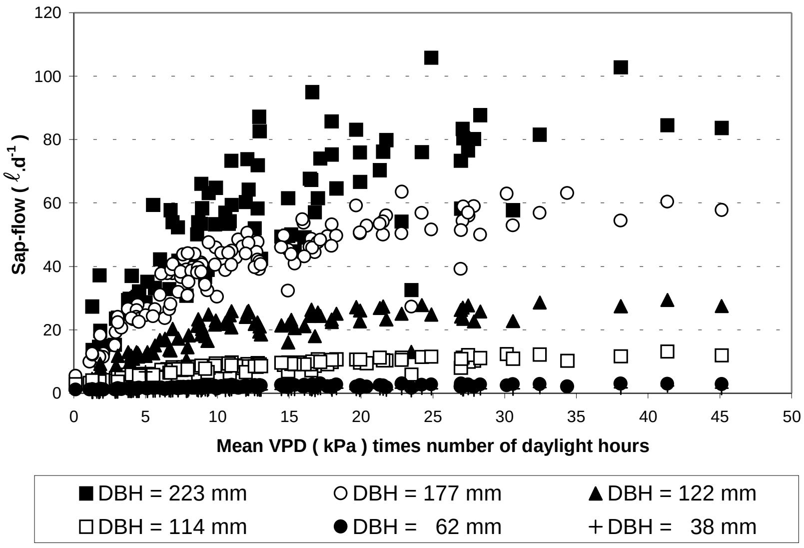

Figure 12
The relation between daily sap flow and the product of VPD and the number of daylight hours recorded at the Groot Drakenstein A. mearnsii *site up to the onset of stress at the end of November*

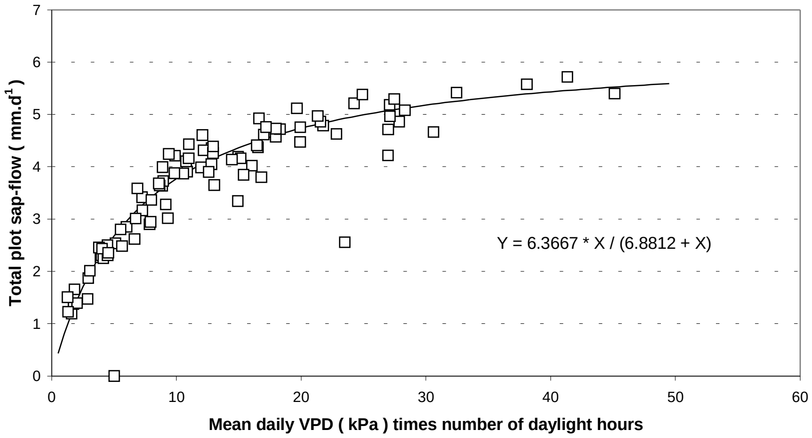

Figure 13
The relation between daily whole-plot sap flow and the product of mean daily VPD and number of daylight hours, measured at the Groot Drakenstein A. mearnsii *site*

We conclude that the removal of riparian wattle and replacement by indigenous herbaceous vegetation may indeed result in significant reductions in annual ET, and may very likely lead to streamflow enhancement. However, this study has clearly shown that annual ET varies considerably in different riparian plant communities, and that one must consider the structural and physiological characteristics of both the pre-clearing and post-clearing vegetation in order to predict the net change in ET. The results of this research cannot be extrapolated to other sites without taking careful account of these factors. The large difference in annual ET between the Jonkershoek fynbos and Gilboa grassland illustrates this point. This difference can be ascribed primarily to different trends of green-leaf area through the year. The Jonkershoek fynbos community remained physiologically active throughout the year, with high, sustained green-leaf areas ensuring high rates of transpiration. By contrast, the grassland at Gilboa was dormant throughout the winter, and water use was below maximum in early and late summer due to reduced green-leaf area. These different patterns of physiological activity are largely responsible for the relatively small annual ET difference between *A. mearnsii* and fynbos at Jonkershoek, and the much larger difference between *A. mearnsii* and grassland at Gilboa.

A. mearnsii ET rates are comparable to closed-canopy plantation forests (Versfeld, 1994; Dye et al., 1997). Canopies remain green throughout the year, and transpiration rates are regulated according to the ambient air humidity and day length. Estimated annual ET estimates for *A. mearnsii* at Jonkershoek and Gilboa differ by 229 mm. This is attributed largely to the different VPD regimes related to the difference in altitude at these sites.

The extent of alien invasive trees in South Africa is so great that land-use managers are often faced with a need to prioritise areas for clearing in order to gain maximum benefit from limited funds. The complexities of prioritising catchments for the clearing of alien invaders have been described by Versfeld et al. (1998) who recognise the water use by alien invasive species as an important data input into the process. A key knowledge gap identified by these authors is a more advanced system for modelling ET of both alien and indigenous plant communities over a wide range of environments and scales. Earlier assessments of the hydrological impacts of alien plants were based on a relatively crude model linking streamflow reduction to above-ground standing biomass (Le Maitre et al., 1996; Van Wilgen et al., 1997). While perhaps adequate for providing a broad national picture, this model is recognised as being inadequate for providing more detailed predictions of water use required for land-use decisions at smaller scale.

Our results demonstrate that relatively simple models based on the most limiting control on the ET of particular vegetation, may be used for predicting ET. This concept is expounded by Calder (1999) and holds great promise as a strategy for expanding our knowledge of ET from diverse vegetation types in South Africa. Such models may be used to simulate ET over several years, thereby taking variable weather conditions into account and providing a more realistic long-term picture of ET for a given type of vegetation. Given the huge variability of South African plant communities (reflecting different species, growing conditions and successional stages), we believe that a modelling system of general applicability will need to take into account the major structural and physiological characteristics that control evaporation of water from plants (green-leaf area, canopy conductance, aerodynamic conductance, soil water availability), as well as the climatic factors governing atmospheric evaporative demand (temperature, relative humidity, solar radiation, wind speed). We recommend that research be initiated to provide such a simple modelling framework to permit rapid assessment of the annual water use of a wide range of vegetation types occurring in areas of the country invaded by alien invasive plants.

Acknowledgements

The Water Research Commission is gratefully acknowledged for funding this project. We acknowledge Cape Nature Conservation for permitting us to work in the upper Jonkershoek Valley, and SAFCOL for allowing ready access to this site, and providing fire-fighting assistance. Mr M. McCabe, owner of Oaklands farm, was most helpful in granting us permission to work on his farm at Wellington, while Mr G. Wagener, General Manager of Anglo American Farms Limited, readily permitted us to work at the Groot Drakenstein site. Mondi Forests also allowed us to work on their Mistley and Gilboa properties, where Mr Mark Chowles and Mr Derek Chard afforded us all the necessary assistance. Dr D. le Maitre kindly undertook the description of the fynbos plant community at the Jonkershoek site, while Dr D. Scott provided the soils descriptions for the Western Cape sites.

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