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Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response

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Black wattle (*Acacia mearnsii*) is one of the most widespread and significant invasive alien trees in South Africa, and great concern is frequently expressed over its potential effect on reducing catchment water yields. The species often forms dense stands, maintains a high green leaf area throughout the year, and frequently replaces seasonally dormant grasslands and fynbos. It is widely accepted that removal of such stands of trees in these circumstances leads to improved catchment water yields. Quantifying this benefit would be useful for analyses of the full economic benefit of alien tree clearing programmes, but relevant information is scarce and scattered in different publications. Streamflow response information is also required to assist in prioritizing areas for alien tree removal. This paper reviews relevant available information on rates of total evaporation from black wattle and from grasslands and fynbos shrublands. These data provide an indication of the likely change in catchment water yield following invasion or clearing of black wattle. The assumption is made that over the long term, reductions in total evaporation equate to water yield increases. Soil water storage and leakage from catchments are therefore considered to be small and constant under the different vegetation covers. Our review shows that very high rates of total evaporation are possible from dense infestations of black wattle occurring in riparian zones, where there are no soil water deficits through the year. Annual total evaporation from such sites may exceed 1500 mm, a figure that is comparable to many evergreen tropical lowland forests. Annual total evaporation from dense stands of black wattle established over entire catchments is likely to be lower than that from trees in riparian zones, since some degree of dry season drought stress is common on non-riparian sites. Annual total evaporation at such sites may exceed the current year's rainfall for a time, if prior accumulation of soil water has occurred. In general, however, low rainfall and low soil water storage capacity will both increase the frequency and severity of drought stress, and restrict annual total evaporation. Annual total evaporation from indigenous grasslands and fynbos shrublands commonly varies over a relatively narrow range of 600 to 850 mm. Differences in total evaporation following invasion or removal of black wattle in such vegetation are potentially large, up to as much as 600 mm. Some indigenous riparian plant communities may, however, demonstrate high year-round rates of total evaporation comparable to those recorded in dense stands of black wattle. The significant feature of such vegetation is the year-round high green leaf area that permits continuously high rates of total evaporation. Streamflow increases following removal of invading black wattles will be greatest in areas of high evaporative demand, where dense stands of trees experiencing low levels of drought stress through the year are replaced by seasonally dormant indigenous vegetation.

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Introduction

This paper presents a synthesis of information on the water use by invasive black wattle (*Acacia mearnsii*) trees in South Africa. Our study provides important additional support for the claim that invasive alien trees can use substantially more water than the indigenous vegetation that they replace. As such, it adds to the body of scientific knowledge, previously limited to data from pine and eucalypt plantations, which underpinned the claim.

Black wattle is the most widespread invasive alien tree in South Africa, and serious infestations occur in the higher rainfall regions of the country.[1] The species commonly invades many forms of indigenous vegetation, developing into dense, evergreen thickets, particularly along riparian zones. The natural vegetation that it replaces commonly exhibits pronounced seasonal dormancy brought about by soil dryness or frost. The potential for increased total evaporation, and therefore reduced catchment water yield, following invasion by black wattle is therefore great.

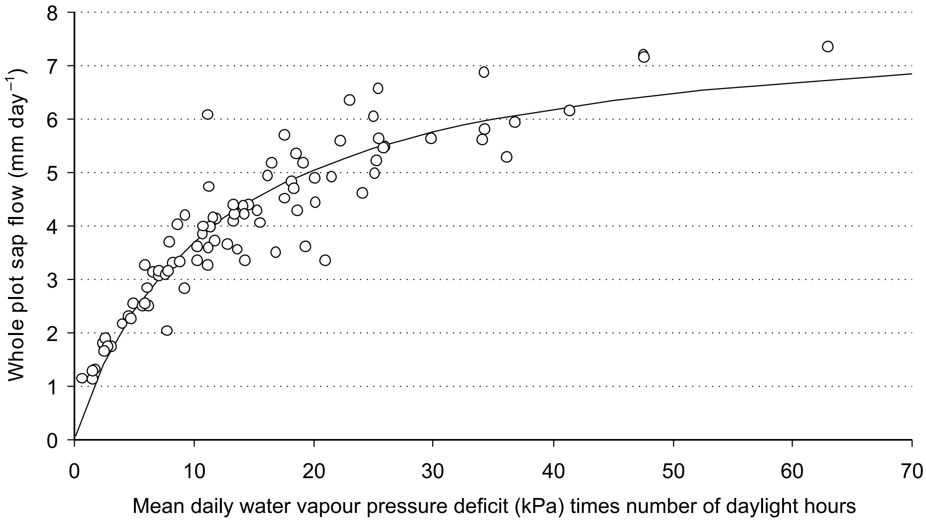

Fig. 1. The relation between whole-plot sap flow and the product of mean daily water vapour pressure deficit and the number of daylight hours, recorded in a riparian stand of black wattle in the Wellington district, Western Cape.[4]

A major justification of the Working for Water programme is the streamflow enhancement that is predicted to follow the control of black wattle and other invasive trees. Several studies of the short-term changes in streamflow immediately following riparian wattle control have been based on measurements of streamflow with portable weirs.[2,3] These have demonstrated streamflow increases immediately after tree felling, but provide an incomplete picture of the longer-term hydrological changes brought about by the removal of the trees. In particular, such measurements do not take into account the rate of total evaporation by the post-clearing vegetation that eventually re-establishes on cleared sites.

This paper reviews patterns of black wattle water use (used here as a general term to describe both transpiration from dry canopies and evaporation from wet canopies, together referred to as total evaporation from stands of trees) recorded at different sites in the Western Cape and the KwaZulu-Natal Midlands of South Africa. Some comparable data for grasslands and certain forms of fynbos shrublands are also presented, to illustrate the possible changes in total evaporation and catchment water yield that are possible when dense infestations of black wattle are removed and replaced by indigenous grasslands or fynbos plant communities.

Water use by black wattle

Several studies aimed at assessing water use by stands of black wattle have been conducted in the Western Cape (at Wellington and Groot Drakenstein) and KwaZulu-Natal (at Seven Oaks). This section reviews these studies and their results.

Wellington, Western Cape

The heat pulse velocity technique was used to record rates of sap flow in six different size classes of trees in a mature, closed canopy, self-established riparian stand of black wattle trees on the farm Oaklands (33°26.084′S, 19°04.892′E) in the Wellington district.[4] Mean annual precipitation in this area is 1050 mm, and the altitude is 345 m above mean sea level (a.s.l.). Hourly measurements were recorded over a 7-month period (August 1997 to February 1998) that covered both wet winter and dry summer conditions. Daily total sap flows recorded in each sample tree were multiplied by the number of trees of the same size class within a demarcated plot, to estimate a whole-plot sap flow (assumed equal to dry canopy transpiration). Daily transpiration of black wattle was found to be closely correlated to the product of mean day-time humidity (expressed as atmospheric vapour pressure deficit) and the number of daylight hours (Fig. 1), illustrating the overriding importance of air humidity and day length in determining daily water use. Maximum daily water use approached 7 mm, a figure that is commonly reported for unstressed forests elsewhere.[5–7] Since no seasonal changes in this relationship were detected, this model is considered useful for predicting the daily water use of dense stands of black wattle under conditions (as in riparian zones) where the trees experience no water stress in any season of the year.

The model was used to estimate the annual pattern of water use by a similar black wattle stand in the Jonkershoek valley (Stellenbosch district, 325 m a.s.l.), on the basis of a 12-month weather record. The resulting dry-canopy annual transpiration was estimated to be 1318 mm. An estimated additional loss of 185 mm due to rainfall interception by the tree canopies yielded a total evaporation of 1503 mm.[4] A similar whole-year modelling exercise at a cooler and more humid high-altitude site (Gilboa, see below) yielded a total evaporation of 1260 mm.[4] The difference in modelled total evaporation between the Jonkershoek and Gilboa sites illustrates the significance of differences in atmospheric evaporative demand in influencing total evaporation from stands of black wattle.

Seven Oaks, KwaZulu-Natal

The Bowen ratio energy balance technique was used to measure rates of total evaporation from a 44.7-ha compartment of plantation black wattle trees in a non-riparian site on Mistley-Canema Estate (Mondi Forests) in the Seven Oaks district.[8] The altitude of the site is 1100 m a.s.l. The trees were planted in June 1996, and before total evaporation measurements were begun, were thinned to 1500 stems per hectare. Twenty-minute rates of total evaporation were continuously monitored over four complete years, from August 1997 to July 2001 (trees aged 1 to 5 years). The leaf area index over most of this period varied between 2 and 3.5. Annual total evaporation was found to be 1240, 1364, 1239 and 1048 mm in the four complete years of measurement, respectively. Annual rainfalls recorded over the same four years were 874, 616, 1016 and 860 mm, respectively. The difference between annual rainfall and annual total evaporation suggests that the trees were using significant quantities of soil water accumulated prior to the time of canopy closure. Peak daily total evaporation around midsummer ranged mostly between 7 and 8 mm (Fig. 2), with only 2.2% of readings exceeding this range. These total evaporation rates are broadly consistent with the sap flow estimates of whole-plot transpiration at the Wellington site.

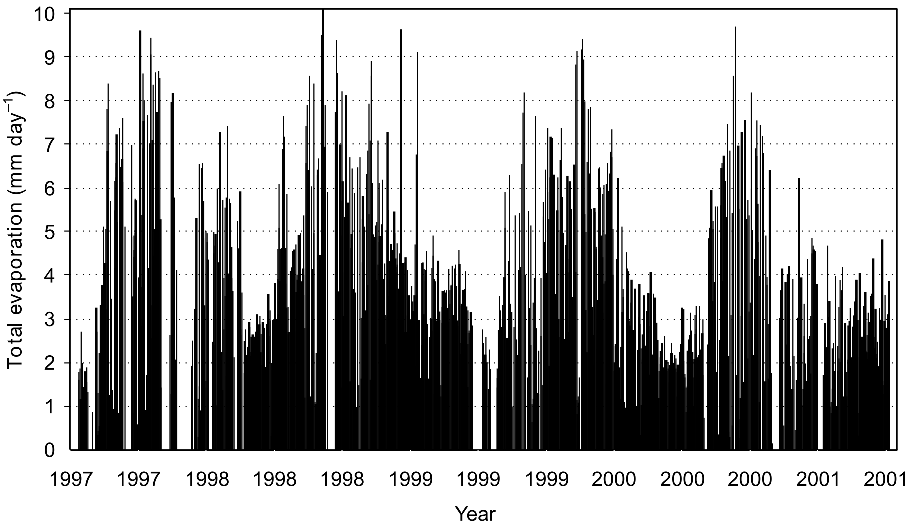

Fig. 2. Patterns of daily total evaporation recorded for a black wattle plantation in the Seven Oaks district, KwaZulu-Natal, for the period 1 August 1997 to 30 July 2001.

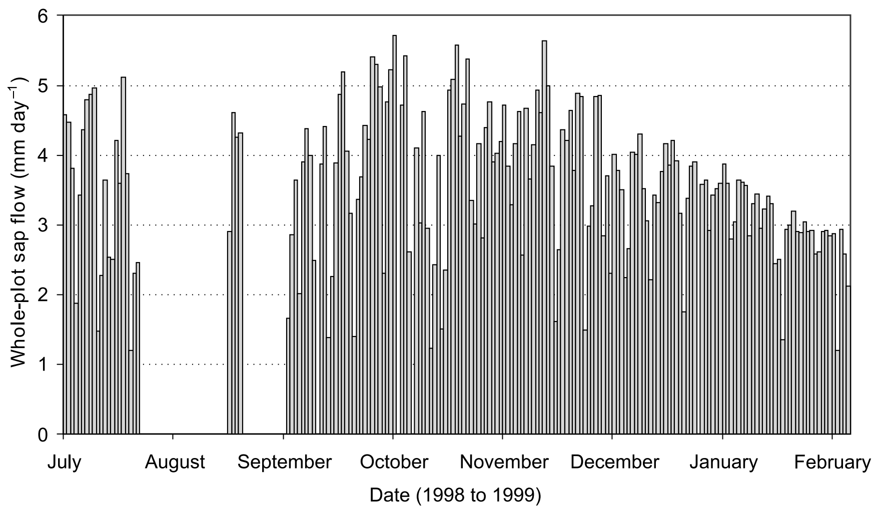

Fig. 3. Daily whole-plot sap flow recorded in a non-riparian stand of black wattle on the slopes of Groot Drakenstein, Western Cape,[4] for the period 25 July 1998 to 24 February 1999.

Groot Drakenstein, Western Cape

A sap flow study based on the heat pulse velocity technique was undertaken in a dense stand of invaded black wattle on the lower slopes of Groot Drakenstein (33°54.595′S, 18°58.530′E; altitude 275 m a.s.l.) in the Pniel district.[4] The sample trees were close to an ephemeral channel that drains the higher mountain slopes. As in the Wellington study, six sample trees were selected to represent the range of tree size found on the site. Daily sap flows recorded in each sample tree were multiplied by the total number of trees of the same size class recorded in a demarcated plot, to arrive at a whole-plot daily rate of transpiration.

Figure 3 illustrates the pattern of transpiration recorded from July 1998 to February 1999. During November and part of December, daily transpiration rates were relatively high, peaking between 5 and 6 mm. From December onwards, daily transpiration progressively declined to about 3 mm, as soil water reserves were depleted. Signs of drought stress were clearly evident in the trees. These results illustrate the importance of soil water availability in limiting the rate of water use by trees growing in non-riparian sites. The decline of total evaporation below potential rates in such environments may reflect not only the immediate soil water deficit, but also additional long-term adaptive reductions in leaf area, stomatal conductance and sapwood structure that limit the rate of water use even in seasons when soil water is plentiful.[9]

Water use by indigenous grasslands and fynbos shrublands

The long-term net influence of black wattle removal on catchment water yield will vary in proportion to the difference in total evaporation between black wattle and the post-clearing vegetation that re-establishes on the site. The larger this difference, the greater the potential increase in catchment water yield. Data from grasslands and fynbos shrubland are reviewed here to illustrate the variability of baseline total evaporation in riparian sites and over entire catchments. Data from Gilboa (KwaZulu-Natal) and Jonkershoek (Western Cape) are presented.

Gilboa, KwaZulu-Natal

A Bowen ratio energy balance system was used to measure hourly total evaporation above a wet grassland within the Inyamvubu vlei (30°15′E; 29°15′S) situated on the Mondi property of Gilboa.[4] This property is situated at the top of the Karkloof hills north of Howick, and lies at an altitude of 1532 m a.s.l.. Mean annual precipitation is 867 mm. The centre of the vlei was under water for much of the summer, but the peripheral area where the total evaporation measurements were taken was inundated for only short periods following substantial rainfall. Figure 4 illustrates the daily pattern of total evaporation at this site. Annual total evaporation was estimated to be 836 mm. This figure is somewhat higher than mean annual total evaporation (666 mm) estimated for short montane grasslands at Cathedral Peak,[10] and may reflect higher evaporation rates during periods of inundation. Growth and water use are strongly seasonal at this site, and this is reflected in the low rates of winter total evaporation and the steep increase and decrease in total evaporation during spring and autumn, respectively.

Jonkershoek, Western Cape

The Bowen ratio energy balance technique was also used to monitor total evaporation above a riparian fynbos community situated in the upper Jonkershoek valley.[4] Peak mid-summer rates of daily total evaporation exceeded 7 mm, and annual total evaporation was estimated to be 1332 mm (Fig. 5). An obvious difference in the pattern of total evaporation recorded at the

Gilboa grassland site (Fig. 4) is the relatively high rates of total evaporation throughout the year, reflecting the fact that the fynbos is evergreen and actively transpiring throughout the year. In contrast, the grasslands are dormant for a part of the year and the low total evaporation rates during winter reflect this. The biomass, cover and leaf area of the Jonkershoek riparian fynbos also greatly exceeds the Gilboa grassland, and this is the likely reason for the generally higher total evaporation rates in the Jonkershoek site. These results highlight the importance of seasonal dormancy and the green leaf area dynamics of plants in determining the annual total evaporation.

Data from gauged catchments, KwaZulu-Natal and Western Cape

Data from gauged research catchments, in both KwaZulu-Natal and Western Cape, have provided useful long-term estimates of whole-catchment mean total evaporation. These estimates are calculated as the difference between annual rainfall and annual total streamflow, assuming that there is no appreciable year-to-year variation in soil water storage, or leakage out of the catchment.

Schulze[11] reports estimated mean annual total evaporation from a number of gauged catchments situated in the KwaZulu-Natal Drakensberg and Midlands regions. These grassland-dominated catchments span a wide annual rainfall gradient (700–1500 mm), but annual total evaporation (Fig. 6) varies from only 600 to 850 mm. Three additional points added to Fig. 6 show the estimated long-term total evaporation from fynbos shrubland vegetation in the Bosboukloof, Biesievlei and Lambrechtsbos B research catchments in the Jonkershoek valley.[12] Total evaporation in these fynbos-dominated catchments varies from 600 to 900 mm per year.

Net changes in total evaporation and streamflow

Figure 7 illustrates the likely changes in total evaporation following invasion or clearing of black wattle in grassland and fynbos-dominated catchments. An analysis of these data illustrates a number of points discussed briefly below.

Very high rates of total evaporation are possible from dense infestations of black wattle occurring in riparian zones, where no soil water deficits occur through the year. Annual total evaporation from such sites may exceed 1500 mm, a figure that is comparable to many evergreen tropical lowland forests.[13]

Annual total evaporation from dense

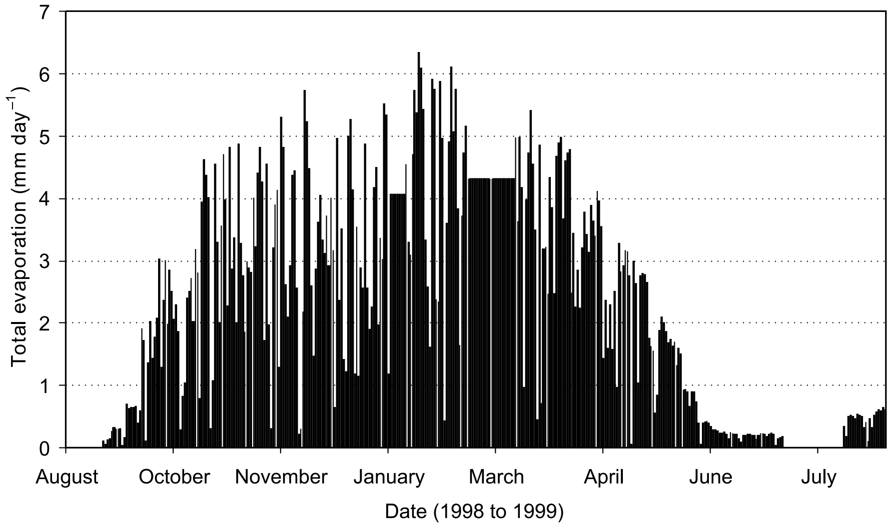

Fig. 4. Daily total evaporation from a seasonally wet grassland at Gilboa, KwaZulu-Natal Midlands, for the period 15 August 1998 to 31 August 1999. Two periods of constant total evaporation contain patched data based on mean daily total evaporation on either side of the data gap.[4]

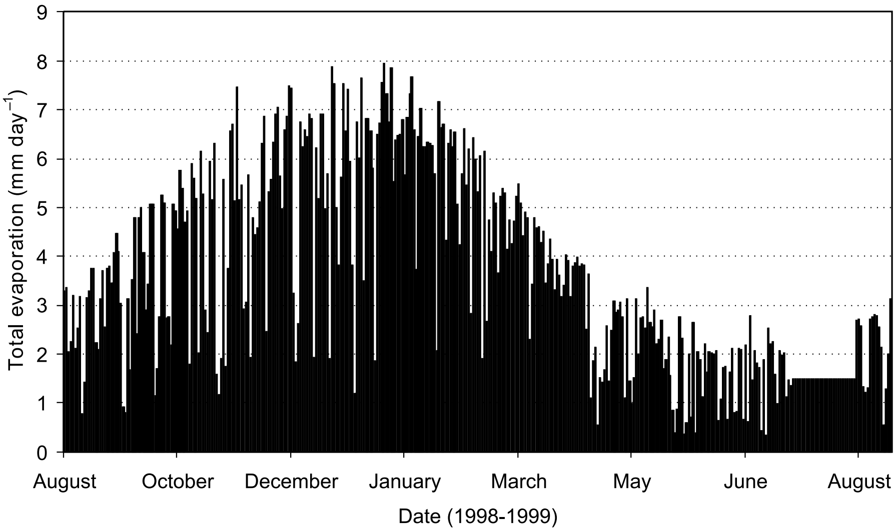

Fig. 5. The annual pattern of total evaporation from a riparian fynbos plant community in the Jonkershoek valley, Western Cape, for the period 26 August 1998 to 25 August 1999. A period of constant total evaporation contains patched data based on mean daily total evaporation on either side of the data gap.[4]

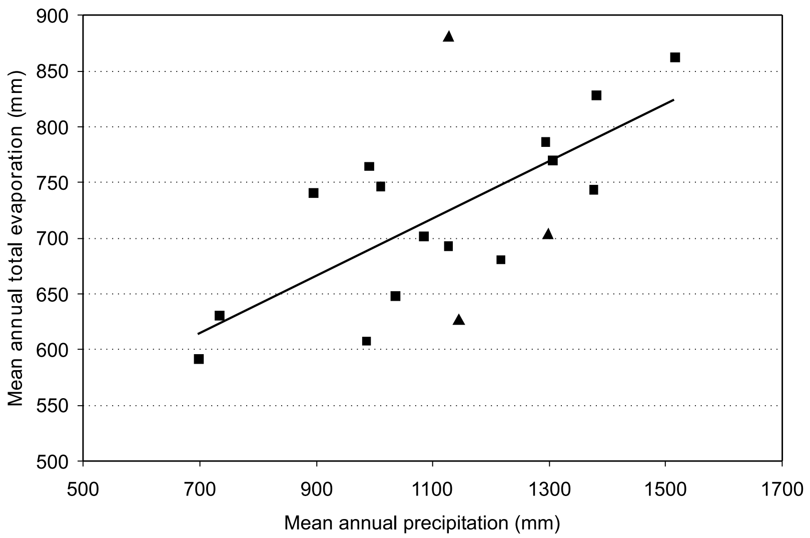

Fig. 6. Mean annual total evaporation estimated for a selection of grassland catchments (■) in KwaZulu-Natal (based on Schulze[11]), and fynbos shrubland catchments (▲) in the Western Cape (based on Scott *et al.*[12]).

invasions of black wattle over entire catchments is likely to be lower than that from trees in riparian zones, since some degree of dry season drought stress is common in non-riparian sites. Annual total evaporation at such sites may exceed the current year's rainfall for a time, if prior accumulation of soil water has occurred. In general, however, low rainfall and low soil water storage capacity will both increase the frequency and severity of drought stress, and restrict annual total evaporation.

Annual total evaporation from indigenous grasslands and fynbos shrublands commonly varies over a relatively narrow range of 600 to 850 mm. Differences in total evaporation following invasion or removal of black wattle in such vegetation are potentially large, up to as much as 600 mm. Some indigenous riparian plant communities may, however, demonstrate high year-round rates of total evaporation comparable to those recorded in dense stands of black wattle. The significant feature of such vegetation is the year-round high green leaf area that permits continuously high rates of total evaporation.

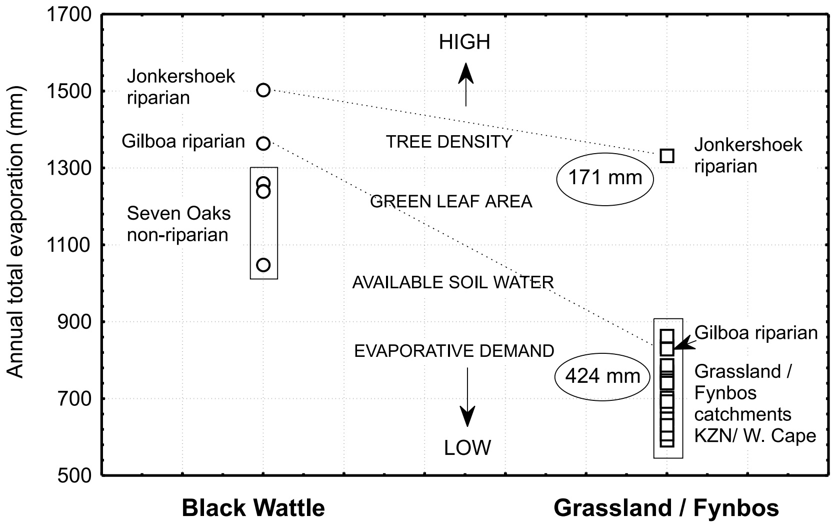

Fig. 7. A chart summarizing annual total evaporation estimated for black wattle and grassland/fynbos vegetation at various sites in KwaZulu-Natal and the Western Cape. The Jonkershoek and Gilboa black wattle estimates are based on model predictions. Major vegetation characteristics governing the net change in total evaporation (shown by the values in ovals) following invasion or clearance of black wattle in grassland and fynbos shrubland catchments are shown in the centre of the chart.

Streamflow increases following removal of invaded black wattle will be greatest in areas of high evaporative demand, where dense stands of trees experiencing low levels of drought stress through the year are replaced by seasonally dormant indigenous vegetation.

Predicting streamflow gains following black wattle control

Black wattle is a widespread and common species in South Africa, and operations to control non-plantation trees are necessarily long-term endeavours. One of the recognized criteria for prioritizing areas for tree removal is the anticipated increase in catchment water yield.[1] While the data described above demonstrate some clear guidelines for predicting changes in total evaporation (and likely streamflow response) for certain vegetation types and conditions, the situation in many invaded catchments is considerably more complex because of varying densities and distribution of invading trees, spatial variation in soil water availability, and highly variable indigenous plant communities. There is a need for affordable, practical methods that would permit the rapid estimation of streamflow response following clearing operations. We believe that remote-sensing techniques have great potential for providing broad-scale information on such vegetation attributes as green leaf area and plant water stress, that strongly influence annual total evaporation. Further research is required to refine existing remote sensing methods to provide the necessary information for modelling the impacts of invasive trees on catchment hydrology throughout South Africa. Towards this end, a current CSIR research project is aimed at recognizing and quantifying drought stress from changed reflectance properties of tree canopies. In a separate initiative, a project funded by the Water Research Commission aims to identify the principal factors governing rates of total evaporation in a wide variety of vegetation types. It is anticipated that the results will provide a framework for predicting total evaporation from any given plant community on the basis of plant structural and physiological characteristics. It is hoped that these two research projects will yield information that greatly improves our knowledge of the hydrological consequences of invasive alien trees.

We gratefully acknowledge the Water Research Commission and Department of Water Affairs and Forestry for funding the research projects that produced the data reported in this paper. Mondi Forests, Cape Nature Conservation, South African Forestry Company Limited, Anglo American Farms Limited, and various private landowners are thanked for giving permission to the research teams to work on their properties.

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