QUANTIFICATION OF THE EVAPOTRANSPIRATION AND STREAM FLOW REDUCTION CAUSED BY BAMBOO SPECIES ON WATER RESOURCES IN SOUTH AFRICA

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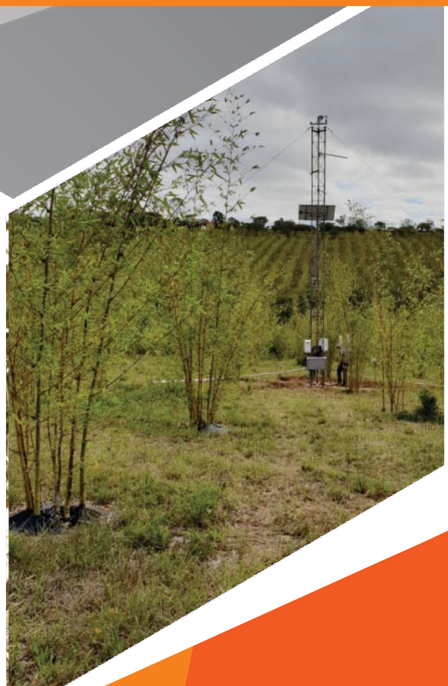

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Report

to the Water Research Commission

by

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EXECUTIVE SUMMARY

In South Africa, the traditional use of energy sources in the form of fuelwood has resulted in substantial negative environmental impacts. The removal of trees for timber and energy has caused the degradation of large parts of South Africa, resulting in poor water infiltration, severe soil erosion and loss of biodiversity. Firewood is the most widely used fuel in many rural areas of South Africa. However, timber is not readily available due to heavy harvesting. One of the potential solutions to this is to convert degraded land into viable bamboo plantations, which will provide timber and fuel to achieve sustainable development.

Bamboo is a grass that mainly reproduces vegetatively through the production of shoots that mature into stems (culms). Culms' function is to conduct water and nutrients from the soil to the leaves. Unlike the culms of most grasses, bamboo's culms have extended woody internodes with intermittent, thickened nodes, which give the bamboo its high tensile strength. In addition, bamboo has a fast growth rate, depending on sufficient resources like sunlight, nutrients and adequate water. If managed correctly, multiple culms are produced annually, which grow into clumps that reach maturity within six to seven years of planting. Not all the culms are removed when harvesting takes place. Generally, a selection of five to six culms from each plant is harvested each year. This ensures that the harvesting is sustainable as the remaining culms will continue to produce new shoots in subsequent years. This process continues for many years.

With this very fast growth rate, high productivity and tensile strength, bamboo has the potential to reduce the deforestation of South Africa's natural forests. Although the bamboo species that have the most potential to solve South Africa's fuelwood crisis are not indigenous, bamboo has been accepted as a naturalised species since its introduction into South Africa during the 1600s (Claassens & Pretorius, 2004).

Bamboo species grow and spread in their habitat through two different growth forms: sympodial growth (clumping species) or monopodial growth through the production of rhizomes (running species). If the planting of bamboo is to be promoted in South Africa, clumping species, which are generally non-invasive, should be selected rather than running species, which may be invasive.

The government, through the Department of Trade, Industry and Competition (DTIC) and the Department of Environment, Forestry and Fisheries (DEFF), is promoting the planting of clumping bamboo species as part of rural agricultural development. However, the water use of this crop is not well understood under South African climatic conditions. According to the Bamboo Association of South Africa, about 40 000 ha is earmarked for bamboo plantations in KwaZulu-Natal and the Eastern Cape. Study sites were therefore selected in each of these provinces.

The amount of evapotranspiration by the relevant species of bamboo should be quantified in South Africa to provide a scientific basis to decide on the status of this crop as a stream flow reduction activity. Understanding the effect of changing land use on water requires knowledge of the natural "baseline" vegetation. Therefore, to compare the water use of bamboo with other species, this study also monitored the water use of natural grassland, eucalyptus trees and wattle trees at the KwaZulu-Natal site.

Knowledge of the water use of bamboo species is also important for its water management to obtain optimum yields. Data must be obtained on the total and seasonal water use to enable the sustainable expansion of the bamboo industry. This is an important requirement to justify or substantiate applications for water use licences for production to be undertaken within official water use authorisations. The aim of this study was to quantify the evapotranspiration and stream-flow reduction impacts of bamboo species on water resources in South Africa and to assess the feasibility of declaring bamboo a potential stream flow reduction activity (SFRA).

The objectives of the study were as follows:

- Determine the evapotranspiration and stream flow reduction (SFR) impact of bamboo species
- Assess the viability of declaring bamboo species a SFRA from a water resource perspective
- Extrapolate the evapotranspiration or SFR results to catchments suitable for bamboo production

STUDY SITES

In KwaZulu-Natal, Shooter's Hill farm, which is located in Otto's Bluff in the Umgungundlovu District Municipality, was selected as the study site. At least 15 different species have been planted on approximately 10 ha on the farm. The second site selected was Kowie farm near Bathurst in the Eastern Cape, where the EcoPlanet Bamboo Company started the first large-scale commercial bamboo cultivation in South Africa in 2012. Some 330 ha of the 485-ha farm has been planted with bamboo. Two clumping species were selected for the study: *Bambusa balcooa* Roth. variety balcooa and *Bambusa balcooa* variety bema.

METHODS

The experimental design of the study comprised a 10 m x 10 m plot at each site, which included representative plants at the different sites. To quantify (scale-up) the water use of these multiple stemmed species, the diameter of each culm of each clump was measured using vernier callipers. At the beema study site in KwaZulu-Natal, 251 culms were monitored, and at the balcooa study site, 72 bamboo culms were monitored. At the Eastern Cape site, 76 culms were measured. In KwaZulu-Natal, growth measurements were also taken of four eucalyptus and wattle trees to determine the growth of the heartwood for calculating the sapwood area for the heat pulse velocity (HPV) water use measurements. The growth information was also used to scale-up the water use data from a single plant to a plantation.

One of the project's main challenges was to determine if the technologies that have been successfully developed to measure the sap flow of dicotyledonous tree species could be applied to monocotyledonous bamboo species, which have scattered vascular bundles near the outside edge of the stem with no pith region. Two different sap flow measuring techniques were used to quantify the water use of bamboo. These were the HPV technique, which quantifies sap flow with respect to depth of temperature probes in a stem, and the stem steady state technique. The latter involves the application of continuous heat energy all around the stem through dynamax collars, which are used to quantify the total sap passing through a fixed area on a stem. Cross-sections of the culms of beema and balcooa were cut, treated and stained for viewing under a scanning electron microscope. The results were used to determine the sap wood area for calculating the transpiration rate.

An automatic weather station was installed at both the KwaZulu-Natal and Eastern Cape sites to measure the meteorological data required to determine total evapotranspiration and short grass reference evaporation, and to interpret sap flow data. In addition, a soil pit was dug at each site and three Campbell Scientific CS616 TDR probes were inserted horizontally at 0.2, 0.4 and 0.7 m, to measure the soil water profile and the hourly volumetric water content.

RESULTS

KwaZulu-Natal

The results from KwaZulu-Natal showed that, during the study period, there was an increase in the total number of bamboo culms in both the beema and balcooa plantations. In the beema plantation, there was an 18% increase in the number of culms, with an additional 38 beema culms (February 2020) from the initial 213 culms measured in September 2018. There was also a 10% increase in the beema culm diameter from a mean of 34.0 ± 5.6 mm (September 2018) to a mean of 37.4 ± 9.5 mm (February 2020).

This increase translated to 0.2 mm month^{-1}. In the balcooa clumps, there was a 12.5% increase in culms, with an additional seven bamboo culms from the initial 56 culms measured in September 2018. The balcooa bamboo culms had a lower increase in diameter (2.6%), from 77.30 ± 14.49 mm in September 2018 to 79.33 ± 14.91 mm in February 2020 (0.12 mm month^{-1}).

By contrast, a decrease in growth was initially recorded in the Eastern Cape, although the difference was not significant. During the 17-month study in the Eastern Cape, the mean culm diameter on 7 February 2019 (19.28 ± 8.69 mm) decreased to 16.74 ±6.39 mm on 12 November 2019 due to the death of some of the culms. At the end of the study on 12 August 2020, the mean culm diameter was 19.37 mm, resulting in a mean growth rate of only 0.005 mm month^{-1}.

The reason for the greater culm size classes and growth in the bamboo growing in KwaZulu-Natal, when compared to that in the Eastern Cape, may be attributed to the differences in rainfall between the two sites. Contrasting the overlapping 17-month measurement periods in the two provinces (November 2019 to May 2020), showed that KwaZulu-Natal had 2 065 mm, compared with only 652 mm recorded in the Eastern Cape. The KwaZulu-Natal site was therefore considered "wet" and the Eastern Cape site "dry". In the Eastern Cape, the annual rainfall for 2019 and 2020 was only 412 and 481 mm, respectively, approximately 200 mm lower than the long-term average of 690 mm. This illustrated the extent of the drought in the Eastern Cape.

Rainfall had a significant impact on the soil water content in KwaZulu-Natal and the Eastern Cape. With high summer rainfall, the total soil water profile content in the KwaZulu-Natal bamboo plantation was ~ 180 mm. When rainfall decreased from 152.7 mm in April 2019 to 7.4 mm in June 2019, the total soil water content declined to ≤ 100 mm. In the Eastern Cape, a reduction in total soil water content from 170 mm in May 2019 to < 80 mm in November 2019 was associated with a decrease in rainfall from 68 mm in May 2019 to a low of 14 mm in December 2019.

In KwaZulu-Natal, the water use of bamboo was closely related to climatic conditions. In February 2019, when the maximum temperature was 32.9 ^{o}C and monthly rainfall reached ~ 230.6 mm, the daily maximum transpiration of the balcooa and beema plantations was ~ 6.0 and > 2.5 mm day^{-1}, respectively. By contrast, a total winter rainfall of only 37.4 mm was recorded from May to June 2019 with temperatures < 18.0 ^{o}C, resulting in low transpiration rates. In the balcooa and beema plantations, transpiration was ~ 2.4 mm day^{-1} and < 2.0 mm day^{-1}, respectively. It appears that bamboo (a grass) was behaving similarly to natural grassland, in that it is a conservative water user during winter. The annual water use of balcooa and beema was 746 and 510 mm respectively. Maximum daily evapotranspiration (ET) rates measured for balcooa in the Eastern Cape were only 3 mm day^{-1} in the summer, contrasting markedly with the KwaZulu-Natal land-use values, which were generally double (6.0 mm day^{-1}). In the Eastern Cape, the annual total evaporation was only 446 and 567 mm for 2019 and 2020, respectively. This was indicative of the dry climate brought about by the severe drought experienced in the Eastern Cape during the study.

The water use of the selected bamboo species was compared with the other land uses at Shooter's Hill: for eucalyptus and wattle plantations. This data was compared with the reference evaporation data collected in the nearby grassland to estimate crop factors.

In the wet summer, peak daily water use in the eucalyptus plantation was ~ 8.0 mm, when energy, temperatures and rainfall were high. This was significantly higher than the daily bamboo water use (~ 5 mm). The results also showed that eucalyptus trees were using > 2.0 mm day^{-1} more soil water when compared with the balcooa plantation. By contrast, in winter, the eucalyptus transpiration rates were reaching ~ 4.0 mm day^{-1}, with an average daily water use of ~ 3.0 mm.

Water use measured in the wattle trees showed that the maximum summer transpiration was higher than in the bamboo plantations (~ 6.0 mm day^{-1}), as well as in winter, when transpiration rates of > 3.0 mm day^{-1} were recorded, with peak winter transpiration rates of ~ 3.5 mm day^{-1}. There was minimal seasonal fluctuation in the wattle's transpiration rates.

The water use of bamboo was modelled by multiplying the calculated reference evaporation (ET_0) by a crop coefficient, K_c. Measured daily transpiration and ET_0 were used to calculate monthly crop coefficients for each land use. This provided a useful comparison of the bamboo species with the other land uses. The K_c values for bamboo were a major input for the Centre for Water Resources Research at the University of KwaZulu-Natal (ACRU)'s SFRA modelling exercise, which was used to assess the SFRA status of bamboo under South African climatic conditions.

The summer daily transpiration values showed that the average K_c in the beema plantation was ~ 0.40 in the wet summer season and 0.49 in the dry winter season. Therefore, the beema plantation had a much lower transpiration than the reference evaporation at Shooter's Hill, indicating that it is a conservative water user. Similarly, the monthly K_c values recorded for balcooa were < 1. By contrast, the higher K_c values for eucalyptus (0.65–1.07) and wattle (0.55–1.28) indicated that they were higher water users than bamboo.

The quantification of the water use of beema, balcooa, eucalyptus and black wattle at Shooter's Hill showed that, under the prevailing climatic conditions during the study, bamboo is a more conservative water user than eucalyptus or wattle. In addition, there was a difference in the water use between the two bamboo varieties, with beema having a lower average transpiration rate (< 1.0 mm day^{-1} in winter and 2.0 mm day^{-1} in summer) compared to balcooa (average = 2.0 mm day^{-1} and 3.8 mm day^{-1} in winter and summer, respectively).

The crop coefficient data generated in this study provided a benchmark of how three-year-old bamboo species used water compared to reference evaporation. The results showed that bamboo species were using at least 40% less water compared to reference evaporation. There were also large differences compared to other land uses such as eucalyptus and wattle in terms of their conservative water use. These results provided a unique data set that was used to determine whether bamboo should be a SFRA.

If the relative impact on runoff exceeds 10%, the proposed land-use change may be declared a SFRA. When this threshold was applied to three scenarios – balcooa planted in KwaZulu-Natal, balcooa planted in the Eastern Cape and beema planted in KwaZulu-Natal – balcooa was considered a SFRA in only < 0.5% of the quinaries, while beema was not considered a SFRA. Therefore, the commercial production of these two clumping bamboo species would be expected to have a minimal impact on stream flow.

FUTURE RESEARCH

This study focused on the water use of three-year-old bamboo plants. Since it is likely that new (larger) shoots will have a higher water use, further studies should be conducted on these culms as they grow and produce larger, more mature culms. Once the harvesting of culms commences, the impact of the selective harvesting of the mature culms will be reduced. This needs to be quantified.

The study in the Eastern Cape was undertaken in two years that experienced less than 200 mm of average rainfall. The extreme drought experienced in the Eastern Cape resulted in the poor development of the bamboo plantations. It is recommended that further long-term studies be carried out to determine the impact of higher rainfall on plant water use in this province. In KwaZulu-Natal, the bamboo growth was not considered water limited, but because of the small areas planted, the sites were not suitable for total evaporation measurements using micrometeorological techniques. Thus, the estimates of water use presented here may be conservative for KwaZulu-Natal. Future research, when more extensive plantings are carried out, will enable a more comprehensive study of their impact on local water resources.

Rainfall interception is an important evaporative loss that should be measured in future interception studies under South African climatic conditions to fulfil this gap in knowledge of bamboo water use. At this stage, only two varieties of the species *Bambusa balcooa* (the beema and balcooa varieties) have been studied over an 18-month time frame. Future research should be extended to include more species over longer time frames.

Since bamboo appears to be a conservative water user, research on the most suitable planting areas for the expansion of the industry should be undertaken to prevent failed investments in the bamboo industry. The SFRA utility developed for this study should be expanded to identify optimum bamboo sites once information on the specific growing conditions of different bamboo species becomes available.

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Mr J Bester	Department of Environment, Forestry and Fisheries
Prof B Kelbe	University of Zululand
Mr G Solomon	Farmer, Shooter’s Hill
Mr A Sutton	South African Bamboo Association
Mr T Newton	EcoPlanet Farm Manager
Dr M Govender	South African Sugarcane Research Institute
Dr R Heath	Forestry South Africa

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ACRU	Centre for Water Resources Research, University of KwaZulu-Natal
ATI	Applied Technologies Inc.
AVRD	Adjustable voltage regulator
AWS	Automatic weather station
CAY	Crop coefficient
COIAM	Coefficient of initial abstraction
COLON	Root colonisation
DBH	Diameter at breast height
DEFF	Department of Environment, Forestry and Fisheries
DEPAHO	Depth of the A-horizon
DTIC	Department of Trade, Industry and Competition
EC	Eddy covariance
E_s	Evaporation
E_t	Transpiration
ET_0	FAO 56 Reference evaporation
ET	Evapotranspiration
F	Sap flux
FC	Field capacity
H	Heat flux
HF	High frequency
H_{fw}	Fine wire thermocouple
H_s	Sonic-derived temperature
HRM	Heat ratio method
HPV	Heat pulse velocity
K_c	Crop coefficient
LAI	Leaf Area Index
MAP	Mean annual precipitation
MAR	Mean annual runoff

M_x	Metaxylem
NRD	Number of rain days
NWA	National Water Act
P	Phloem
PAW	Plant available water
PCSUCO	Percentage surface cover
PWP	Permanent wilting point
RH	Relative humidity
ROOTA	Root fraction in A-horizon
S	Sap velocity
SEM	Scanning electron microscope
SFR	Stream flow reduction
SFRA	Stream flow reduction activity
SR	Surface renewal
SSS	Stem steady state
SWC	Soil water content
TDP	Thermal dissipation probe
TSPWC	Total soil profile water content
VEGINT	Interception loss
V_h	Heat velocity
VPD	Vapour pressure deficit
VSWC	Volumetric soil water content
VWC	Volumetric water content

REPOSITORY AND STORAGE OF DATA

REPOSITORY OF DATA

For details related to the project's data, please contact:

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DATA STORAGE

The project has generated over 1 GB of hourly heat pulse velocity data, as well as high-frequency temperature and wind speed data collected from March 2019 to December 2020 for two sites, one in KwaZulu-Natal and the other in the Eastern Cape. The data was analysed to estimate the evapotranspiration for two bamboo species, from which monthly crop coefficients were derived. The crop coefficients were used to generate over 30 GB of compressed ACRU output pertaining to the national model runs to estimate bamboo's water use and runoff generation. The latter was used to determine if bamboo should be declared as a potential stream flow reduction activity (SFRA). The SFRA software utility was used to disseminate the large database of monthly runoff simulations for natural vegetation and three bamboo scenarios. All raw, processed and modelled data is stored and archived on a fileserver located in the ICS server room on the University of KwaZulu-Natal's main campus in Pietermaritzburg.

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CHAPTER 1: INTRODUCTION

With the increasing impacts of global climate change, the depletion of natural resources and the increased degradation of the world's environment, there is a need for more sustainable development. Sustainable development and growth can be achieved by the improved management of ecosystems and the more strategic use of water, land and other natural resources such as trees. In South Africa, the traditional use of energy sources in the form of fuelwood has resulted in substantial negative environmental impacts. The removal of trees for timber and energy has caused the degradation of large parts of South Africa, resulting in poor water infiltration, severe soil erosion and loss of biodiversity. Biomass, particularly firewood, is the most widely used fuel in many rural areas of South Africa. However, timber is not readily available anymore due to heavy harvesting. This has resulted in the degradation of large areas, causing environmental problems, as well as social concerns, with poor households being unable to purchase timber from outside sources. If sustainable development is to be achieved, it will be necessary to seek alternative options and technological innovations to improve the efficiency of timber harvesting, as well as to find solutions to economic and environmental problems associated with timber shortage.

One such innovation is to convert degraded land into viable bamboo plantations. which will provide timber and fuel to achieve sustainable development. The sustainability of bamboo is related to its fast growth rate and vegetative growth pattern, which produces shoots (tillers) that mature into stems (culms). The function of these culms is to conduct water and nutrients from the soil to the leaves. They are characterised by extended woody internodes with intermittent, thickened nodes, which give the bamboo its high tensile strength. If managed correctly, multiple culms are produced annually. These culms grow into clumps that reach maturity within six to seven years of planting. Not all the culms are removed when harvesting takes place. Generally, a selection of five to six culms from each plant is harvested each year. This ensures that the harvesting is sustainable as the remaining culms will continue to produce new shoots in subsequent years. This process continues for many years.

With this very fast growth rate, high productivity and tensile strength, bamboo has the potential to reduce the deforestation of South Africa's natural forests. However, the bamboo species that have the most potential to solve South Africa's fuelwood crisis are not indigenous. Nevertheless, it must be acknowledged that some alien plants are an important contributor to the economy and there is a place for them in agricultural systems. Bamboo plantations in South Africa have the potential to create employment, provide viable economic and resource outputs and contribute to poverty alleviation and carbon sequestration. However, in spite of growing public and private investment, little is known about the opportunities, challenges and impacts of commercial bamboo growing in Africa (Scheba et al., 2018).

The government, through the Department of Trade, Industry and Competition (DTI) and the Department of Environment, Forestry and Fisheries (DEFF), is promoting the planting of bamboo species as part of rural agricultural development. According to the Bamboo Association of South Africa, about 40 000 ha is earmarked for bamboo plantations in both KwaZulu-Natal and the Eastern Cape. However, the water use of this crop is not well understood under South African climatic conditions. Therefore, the amount of evapotranspiration by the relevant species of bamboo should be quantified in South Africa to provide a scientific basis to decide on the status of this crop as a stream flow reduction activity (SFRA).

Knowledge of the water use of bamboo species is important for its water management to obtain optimum yields. Knowledge must be obtained of the total and seasonal water use to enable the sustainable expansion of the bamboo industry. This is an important requirement to justify or substantiate applications for water use licences in order for production to be undertaken within official water use authorisations.

Knowledge of water use is also required to motivate the periodic review of water use licences for the long-term production of bamboo. Following an analysis of current initiatives and potential plantings of bamboo species in South Africa, together with advice from farmers, the government and commercial enterprises, the following species were selected for this study:

- *Bambusa balcooa* (variety balcooa)
- *Bambusa balcooa* (variety beema)

Understanding the effect of changing land use on water requires knowledge of the natural “baseline” vegetation. In order to compare the water use of bamboo with other species, this study also monitored the water use of *Eucalyptus grandis* (eucalyptus), *Acacia mearnsii* (wattle) and natural grassland.

The aim and objectives of the research study are as follows:

1.1 AIM

To quantify the evapotranspiration and stream flow reduction impacts of bamboo species on water resources in South Africa and to assess the feasibility of declaring bamboo as a stream flow reduction activity.

1.2 OBJECTIVES

- Determine the evapotranspiration and the stream flow reduction (SFR) impact of bamboo species
- Assess the viability of declaring bamboo species a SFRA from a water resource perspective
- Extrapolate the evapotranspiration or SFR results to catchments suitable for bamboo production

CHAPTER 2: LITERATURE REVIEW: THE WATER USE OF BAMBOO AND SPECIES DISTRIBUTION IN SOUTH AFRICA

2.1 HISTORICAL BACKGROUND OF BAMBOO SPECIES

Bamboo, a perennial monocotyledonous woody grass species (Awalluddin et al., 2017), was historically known as poor man's timber and a traditional plant species. However, in recent times, it has been regarded as a wonder "green gold" plant due to its numerous uses. It is of growing interest to the scientific community (Laplace et al., 2017). Bamboo is a Poaceae (Bambusoideae) family grass species and constitutes about 88 genera and 1 500 identified species in the world (Awalluddin et al., 2017). Awalluddin et al. (2017) also indicated that more than 70 genera grow naturally in temperate, tropical and subtropical regions (Figure 2-1). This was also supported by Tsuruta et al. (2016), although other scientific works have indicated that the identified species have reached 1 662 in 121 genera (Canavan et al., 2017).

Bamboo is native to Asia, growing predominantly in south and southeast Asia. It comprises about 80% of different bamboo species in the world, with Brazil and Australia following China as the countries with the highest bamboo richness (Figure 2-2). Ying et al. (2016) showed an expansion in bamboo plantations of 161% between 1984 and 2014 in Tianmushan, Zhejiang Province, China. However, the study also indicated a 20% decline in recent years due to human activities such as deforestation (Ying et al., 2016). The value of bamboo is in its multiple uses. Bamboo's main use is as a construction material. Awalluddin et al. (2017) indicated that hardened culms of *Bambusa vulgaris*, *Gigantochloa scortechinii* and *Dendrocalamus asper* have higher tensile and compressive strength than most timber.

The tensile strength of different bamboo species in relation to their usefulness as a construction material is shown in Table 2-1. They are a good substitute for steel and timber, as the plants are more economical and environmentally friendly, and unlike the manufacture of steel, do not contribute significantly to the increase of dangerous gases to the atmosphere.

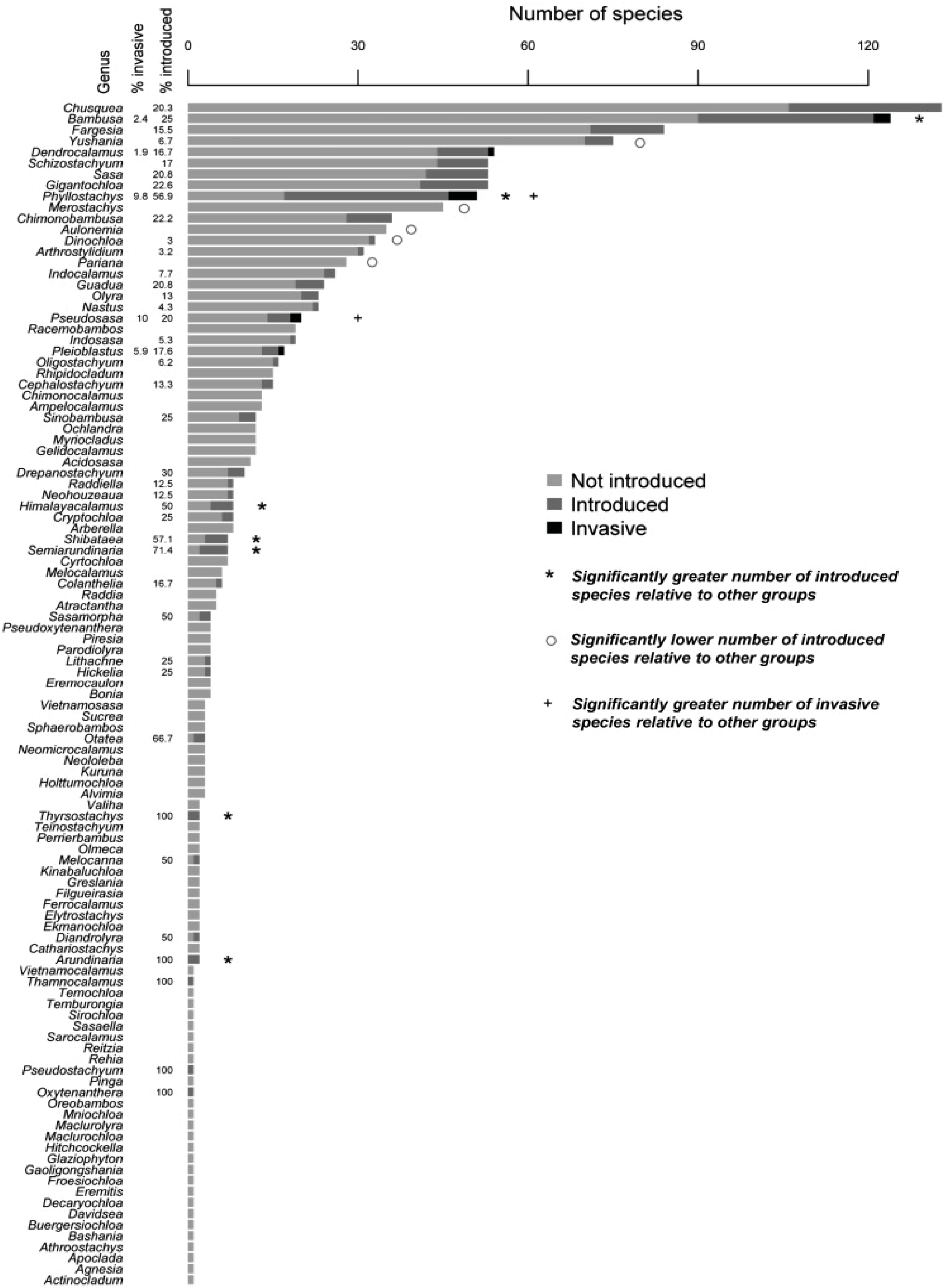


Figure 2-1: Bamboo species within genera and species status (Canavan et al., 2017)

The fresh shoots of bamboo are also a good source of nutritious food and are consumed fresh, canned, pickled, cooked or fermented, with potential growth in the food processing industry where it is produced on a commercial scale (Amlani et al., 2017). Bamboo culms have been used for paper manufacturing (Amlani et al., 2017). The bamboo industry that produces paper has been in existence for over 2 000 years, showing that the species is reliable for paper production (Shroti et al., 2012). Bamboo can also serve as an energy source in Africa, substituting for the use of fossil fuels that cause air pollution, deforestation and the depletion of the ozone layer because it provides clean energy, and viable and sustainable wood fuel (Sette Jr et al., 2016). Bamboo species are widely used for biofuel synthesis. The switch from fossil fuel to bamboo fuel was caused by a drastic reduction in the availability of fossil fuels and the environmental protection act that required an alternative to fossil fuel due to extensive land degradation that affected biodiversity (Fatriasari et al., 2014). A study by Bebbington et al. (2018) also showed that there is, indeed, an extreme reduction in total forest areas in the world with regard to human intervention through deforestation and land degradation. However, because of bamboo's sustainable characteristics and its fast growth, bamboo plantations had less of an effect on destroying land, and that bamboo forests have been increasing compared with the decrease in coniferous forests (Xu et al., 2020). Currently, bamboo production is expanding tremendously and new food products, such as bamboo juice, bamboo vinegar and clothing items made from the fibre extracted from the culms, as well as bamboo coal, are being derived from various bamboo species (Amlani et al., 2017).

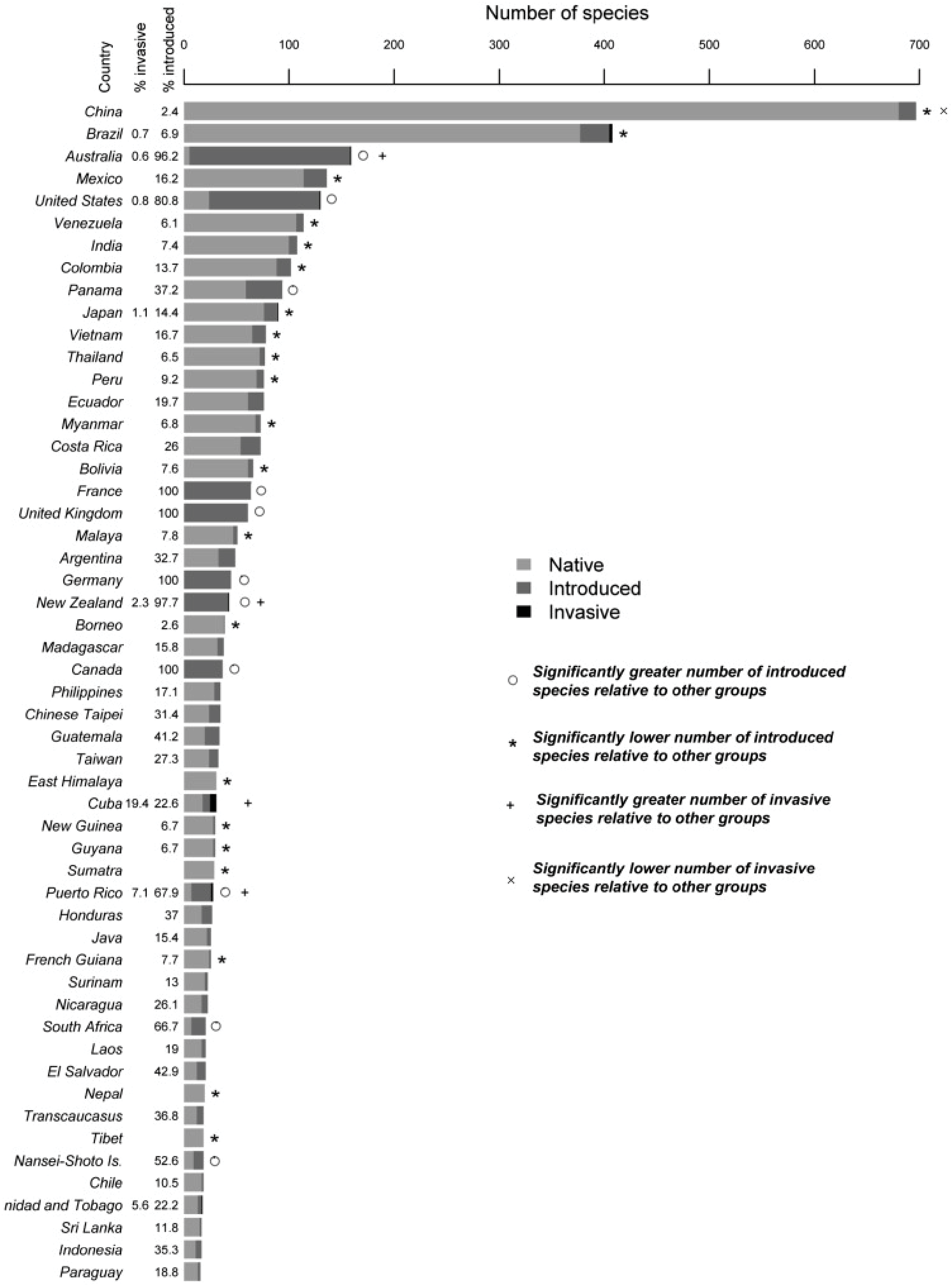


Figure 2-2: Countries and islands with the highest bamboo richness (Canavan et al., 2017)

Bamboo species comprise different growth forms, including giant woody species and understory herbaceous species (Canavan et al., 2017; Mulkey, 1986). Bamboo species grow and spread in their habitat through two different growth forms: sympodial growth (clumping) (Figure 2-3) or monopodial growth (runner bamboo rhizome structures) (Figure 2-4).

Floral structures are only visible once in a 40- to 80-year period because bamboo only flowers once in its lifetime (it is semelparous), at which time seeds may or may not develop. These taxa exhibit mass flowering (or gregarious flowering), with all plants in a particular cohort flowering over a period of several years. This encourages vegetative propagation. The flowers are subdivided into two categories: dendrocalamus, known as the closed structure, and bambusa, known as the open floral structure, although these characteristics may also be species dependent (Das et al., 2017). Herbaceous bamboo species are generally temperate species and thrive in regions where there is less sunlight or cool air temperatures (Canavan et al., 2017). By contrast, the giant woody species (e.g. *Pharus latifolius*) that prefer exposure to sunlight are predominant in tropical and subtropical regions, where they can optimise their photosynthetic ability due to the high radiation levels in low-altitude regions (Mulkey, 1986).

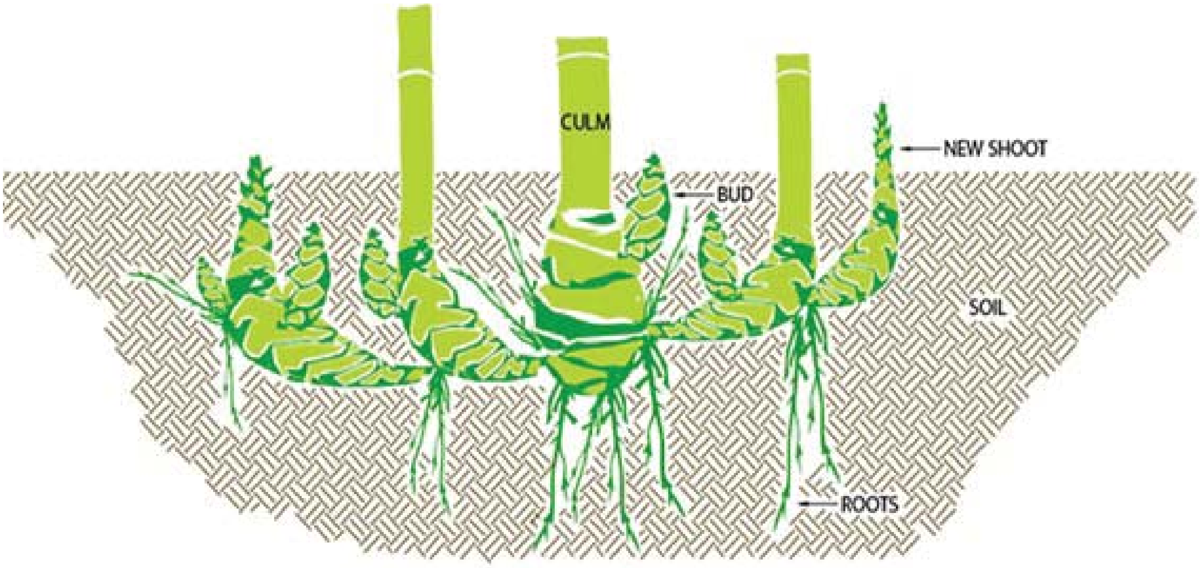


Figure 2-3: The rhizome anatomical structure of sympodial bamboo species (Bamboo Botanicals, 2019)

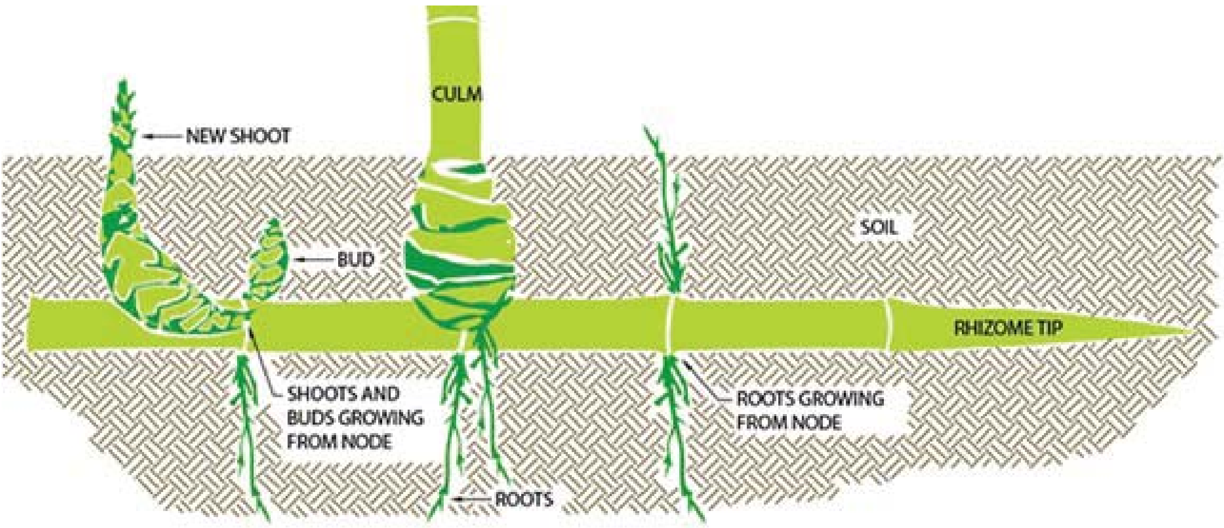


Figure 2-4: The rhizome anatomical structure of monopodial bamboo species (Bamboo Botanicals, 2019)

Species that grow through monopodial rhizomes are very invasive and tend to be a great threat to the hydrological cycle in a forest (Viana & Filgueiras, 2014). Depending on sufficient resources, like sunlight, nutrients and adequate water, some bamboo plants have a fast growth rate and can reach a height of 30 m within four months (Awalluddin et al., 2017).

This fast growth rate and the highly developed rhizomes beneath the soil surface can result in the development of numerous culms and shoots that form dense stands and tend to overcrowd (Xu et al., 2020) and compete with other species within the forest habitat for water, sunlight and nutrients. Depending on the type of species and rhizome structure, running bamboo (leptomorph) are invasive, aggressive and form long thread rhizomes that extend into water sources, unlike the non-invasive clumping bamboo (pachymorph), which forms thick and dense rhizomes that are fixed within the cultivated area (Guanglu, 1988).

According to reports, poor management of bamboo plantations has resulted in large impacts on the water resources in many countries. Some reports indicated that bamboo plantations were even abandoned in the early centuries because there was little knowledge concerning management practices and the industrial use of the plant (Tsuruta et al., 2016).

However, subsequent research studies and the increase in bamboo production have shown that the previously abandoned plantations are now properly managed and rural communities are benefiting from productive bamboo plantations. However, more information is needed on the water use of bamboo. Fresh bamboo shoots are largely constituted of water, which indicates the importance of understanding the relationship between bamboo growth and development with water uptake, especially in the early growth stages.

This relationship is important in understanding its impact on stream flow reduction and the effect of species on the hydrological cycle. This review aims to describe the characteristics of the different bamboo species in the world, especially those that are cultivated on a commercial scale in South Africa, and to highlight how these species may affect the local hydrological cycle in comparison to other commercially grown forest species. Understanding this relationship will assist in decision making on whether expanding bamboo plantations on a commercial basis will be ideal in the context of the limited water available in the country.

Table 2-1: Comparison of culm area (mm^2) and tensile strength ($N\ mm^{-2}$) of bamboo species (Awalluddin et al., 2017)

Bamboo species	Average culm area (mm^2)			Tensile strength (Nmm^{-2})		
	Top	Middle	Bottom	Top	Middle	Bottom
Dendrocalamus asper	89.47	98.09	112.96	232.80	200.75	232.31
Bambusa vulgaris	57.31	61.29	67.20	231.67	233.98	230.63
Gigangochloa scortechinii	49.30	48.50	53.04	187.67	144.92	176.22
Schizostachyum grande	48.21	49.18	49.50	149.20	114.93	113.01

2.2 COMMERCIAL MONOPODIAL BAMBOO SPECIES

Monopodial plants are typically bamboo species characterised by thin rhizomes that grow horizontally in the soil surface and can extend for distances, causing an impact on water resources and competition with nearby species for sunlight, water and nutrients.

2.2.1 Subtropical and tropical bamboo species

The following species are typical bamboo species that thrive in warmer temperatures, especially areas with mean temperatures of around 18 ^{o}C annually.

2.2.1.1 Canebrake (*Arundinaria gigantea*)

River cane or canebrake, scientifically known as *Arundinaria gigantae* (Walter) Muhl., is among the the most accredited eastern North American bamboo species. It is one of the three native temperate bamboo species of North America that grows along stream banks in moist clayey soil types and at forest edges where soils are water saturated (Krayesky & Chmielewski, 2014; Neal et al., 2012).

Canebrake serves as a habitat for various wildlife species, especially threatened species (e.g. arthropods, birds and mammals). The populations of these species are drastically declining because of river channelisation, agricultural practices and land degradation (Brantley & Platt, 2001; Dattilo & Rhoades, 2005). Cirtain (2004) reported that many of the canebrake species are already extinct because of human impact on the environment. This is supported by various studies, which have shown that this species' extinction has subsequently affected biodiversity in these areas (Neal et al., 2012). Other studies have indicated that, since the 18th century, about a 98% reduction has been observed in canebrake species in North America. This has to be fixed, according to Brantley and Platt (2001). Therefore, many studies have been initiated to investigate how the remaining species can be preserved and produced in large quantities to counteract the decline in threatened species because of habitat loss (Cirtain, 2004).

Canebrake species, like other bamboo species, are semelparous (i.e. characterised by a single reproductive episode before death), only flowering once in a lifetime. Longevities of 20 to 100 years before the development of floral structures make it difficult to propagate the species through seeds. Therefore, studies have been initiated to investigate alternative methods of propagation. Scientific research has shown that an alternative to seed propagation is to cultivate canebrake species by means of rhizome and culm cuttings (Krayesky and Chmielewski, 2014).

Nevertheless, this has proven to have limitations due to the poor establishment of vegetative shoots, especially after transplanting from the nursery (Cirtain, 2004). Canebrake establishment has the potential to improve the water quality in catchment areas and control soil erosion caused by excess runoff, which erodes topsoil containing organic matter, chemicals and foreign substances (Cirtain et al., 2009).

Through soil stability and stream bank stabilisation, the species is said to be of high importance for improving water quality (Neal et al., 2012). Therefore, the reduction in canebrake distribution not only affects biodiversity, but also compromises water quality and quantity.

2.2.2 Temperate bamboo species

The following species are typical bamboo species that thrive in cold temperatures, especially areas with annual temperature ranges from -3 to 18 ^{o}C:

2.2.2.1 Moso bamboo (*Phyllostachys edulis*)

The rate of burning of fossil fuel in the production of various industrial products has increased significantly over the past two decades. This is primarily influenced by market demand and the creation of millions of jobs in the world. Nevertheless, depositing and burning fossil fuel contributes to the presence of various toxic gases in the atmosphere, such as carbon dioxide, methane and nitrous oxide. These gases trap heat from escaping the earth's surface, resulting in global warming and rises in atmospheric temperature (Seethalakshmi et al., 2009). Extreme temperatures have many consequences, including coral bleaching in the sea due to a reduction in the sea level. They may also cause a reduction in freshwater and subsequent health complications (Lowe et al., 2016), loss of biodiversity (Hughes et al., 2003), and a breakdown of the trophic pyramid (McMichael et al., 2006).

Associated with burning fossil fuels is the high rate of deforestation and land degradation that contributes to extreme gas concentrations in the atmosphere. These effects have led to research studies on reducing the levels of these toxic gases to the atmosphere by substituting fossil fuels for renewable and sustainable plant species that are environmentally friendly and capture high amounts of carbon dioxide. Bamboo is a good and reliable source of energy (e.g. Moso bamboo).

Moso bamboo, scientifically known as *Phyllostachys edulis,* is a useful bamboo species that is utilised for energy. It is characterised by its ability to fix high carbon dioxide concentrations from the atmosphere (Chen et al., 2018). The species grows very quickly and serves as a good source of nutritious food.

Moso bamboo is a temperate woody bamboo species native to East Asia, but was domesticated in the subtropical and tropical regions of China as early as 1700 to be cultivated commercially (Shinohara et al., 2013). Currently, it has occupied over 73.8% of China's forest area (Chen et al., 2018), and about 10% of India's forest area (Shinohara et al., 2013). Moso bamboo has been used intensively for construction purposes and food production. Nevertheless, many industries have used the plant to manufacture paper and pulp.

In addition, the species is a good source of charcoal, replacing coal, the mining of which causes severe land degradation and water pollution through acid mine drainage (Onozawa et al., 2009). These characteristics make Moso bamboo a plant with a high economic value. However, its extensive use has led to concern over its impact on water resources. Research has therefore been conducted to investigate the water use of the Moso bamboo species at different growth stages to evaluate its hydrological effect. A study by Komatsu et al. (2010) indicated that these bamboo plants consume large amounts of water for growth and development when compared with neighbouring coniferous plantations. This study found that the species exceeds coniferous water use by 12%. By contrast, Shinohara et al. (2013) and Onozawa et al. (2009) reported a lower water consumption (10%) than the coniferous plantation. They concluded their studies by promoting the commercial production of Moso bamboo.

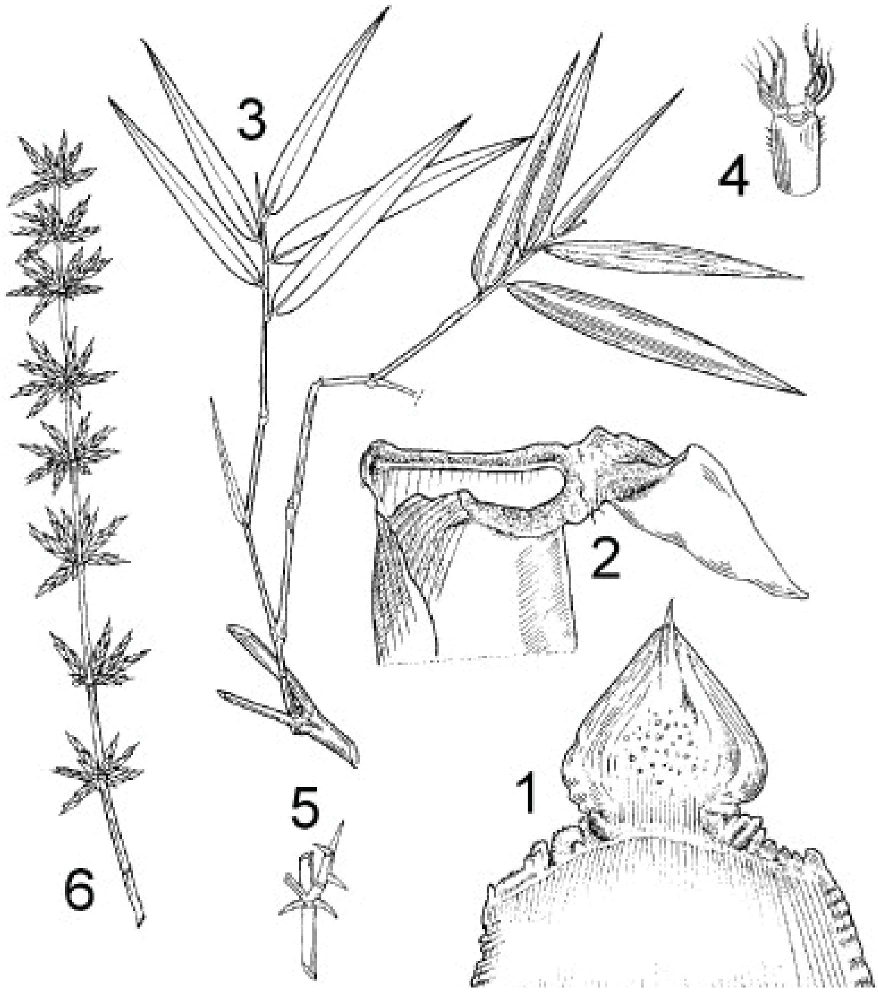
2.3 COMMERCIAL SYMPODIAL BAMBOO SPECIES

2.3.1 Subtropical and tropical bamboo species

2.3.1.1 Giant thorny bamboo (*Bambusa bambos*)

The giant thorny bamboo (Figure 2-5), also referred to as *Bambusa bambos* (L.) Voss, is a southeast Asian bamboo, with a clumping growth habit. It grows in the tropical regions of Asia. The species is widely cultivated throughout the Western Ghats Mountains of India because of its good mechanical properties and environmental impact on increasing carbon dioxide fixation and bee collection (Koshy et al., 2001). Figure 2-6 illustrates the distribution of the giant thorny bamboo throughout India and Asia, showing a high population of the species in Asia, especially around Myanmar, Cambodia and Thailand.

The giant thorny bamboo has high levels of silica, which can be extracted and used to manufacture medicinal products that cure osteoarthritis. The species is also highly recommended for construction, making it an economically valued plant in the rural areas of Kerala, India (Kumar et al., 2006), especially because of its intensive potential for high biomass accumulation (Gupta & Kumar, 2008). Studies have indicated that the giant thorny bamboo also has a high ability to withstand salt-concentrated environments and salty water (Pulavarty & Sarangi, 2018), making it a useful plant in salt-concentrated environments where other plant species cannot grow. There are only a few studies on the impact of the commercial cultivation of this species. Research on the ecological importance and industrial use of the species for various products is therefore recommended.



1. Culm leaf (abaxial side); 2. Culm leaf (side view); 3. Leafy branch; 4. Top of leaf sheath with ligule and auricles; 5. Part of the branch with spines; 6. Flowering branch

Figure 2-5: The plant structures of the giant thorny bamboo (*Bambusa bambos*) (CABI, 2019)

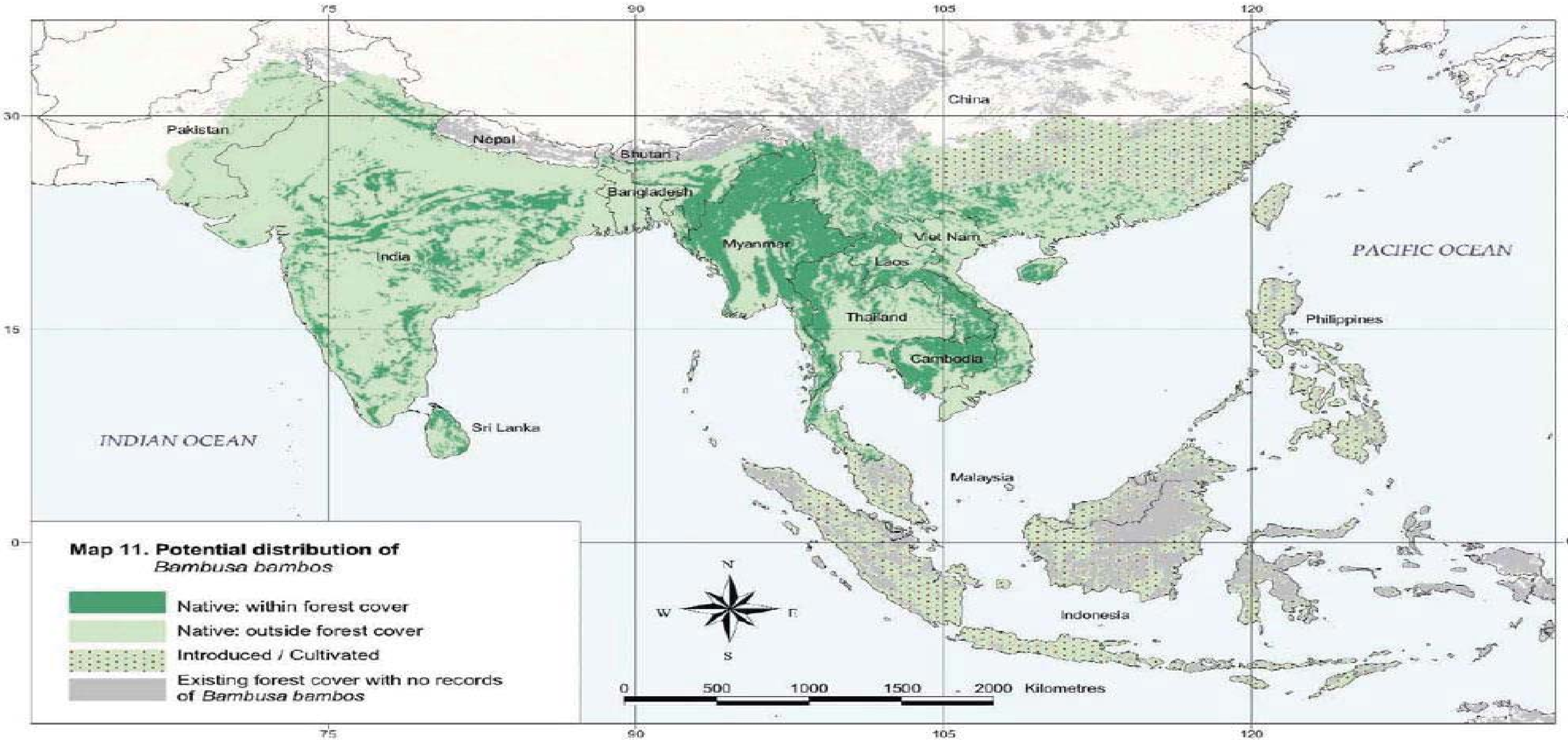


Figure 2-6: Geographic distribution of *Bambusa bambos* in India and Asia (Schröder, 2007)

2.3.2 Temperate bamboo species

2.3.2.1 Hardy bamboo (*Fragesia rufa*)

The evergreen sympodial bamboo species known as hardy bamboo (*Fragesia rufa* Yi.) is a temperate bamboo that is native to China. The species grows as an understory in the coniferous forests of China. It is shade tolerant and withstands low temperatures (Liu et al., 2017). Hardy bamboo is a dwarf structured bamboo species with a shallow root system (Plate 2-1), making the species mostly dependent on saturated soil conditions (Liu et al., 2015). The species normally grows along streams under coniferous plantations to access water easily. A study by Liu et al. (2017) indicated that hardy bamboo cannot withstand dry environments with low rainfall where their roots cannot access water easily. This has negative consequences in unfavourable growing conditions, which cause early flowering, leaf abscission and premature death.

Fragesia rufa serves as the main source of nutritious food for forest pandas. Therefore, temperature increases, river channelisation and urbanisation, which adversely affect water availability, have a negative effect on forest panda populations because of food scarcity. Transplanting has therefore been implemented as a means to prevent the extinction of hardy bamboo and conserve panda species (Liu et al., 2015).

Plate 2-1: Hardy clumping bamboo (*Fragesia rufa*) root structure (Vaupel, 2005)

2.4 COMMERCIALLY GROWN BAMBOO SPECIES IN SOUTH AFRICA

The following species are commercially grown in South Africa for industrial purposes and in large areas in both KwaZulu-Natal and the Eastern Cape:

2.4.1 Balcooa (*Bambusa balcooa*)

Bambusa balcooa Roxb. (Bambusoideae) is a tropical clumping species that is indigenous to India (Ray & Ali, 2016). It is an economic investment plant due to its multiple uses in industry for paper and pulp production (Sharma & Sarma, 2011), and can be processed to produce biofuel, syngas and charcoal (Truong & Le, 2014). Balcooa has gained popularity in South Africa recently. Globally, the species serves as a good source of nutritious food consumed in most regions of Asia and China, especially in rural areas (Ray & Ali, 2016).

Due to its nutritional value, there has been a growth in bamboo food production industries and the bamboo pickle industry (Sharma and Sarma, 2011). In ancient times, this species was only popular with rural communities as a source of food and as poor man's timber. Recently, industries have been encouraging the cultivation of balcooa bamboo species for the wider consumption of various food products.

Studies have indicated that the species has the potential to grow up to 25 m in most favourable environments under tropical humid climatic conditions (Upreti and Sundriyal, 2001), and in moist flat alluvial environments with altitudes of 1 500 m above the sea level (Sharma and Sarma, 2011). The cultivation of this species has the potential to improve climatic conditions because of its high potential for carbon sequestration, which can be used to ameliorate negative anthropogenic effects on the environment. It can be cultivated worldwide to improve climatic conditions by reducing carbon dioxide concentrations of up to 17 tons per year per hectare of bamboo plantation (Seethalakshmi et al., 2009). This can also improve air quality and oxygen concentrations, and reduce air pollution (Seethalakshmi et al., 2009). Moreover, agricultural industries have adopted cultivating the species as a means of reducing high wind velocities that affect cultivated crops by causing lodging and fruit drops before fruit maturity. It also has the potential to improve soil stability and soil properties (Amlani et al., 2017).

There have also been studies aimed at developing effective propagating techniques for *Bambusa balcooa* that allow optimum growth, and plant tolerance to various conditions and diseases, and promote growth at a fast rate for sustainability (Negi and Saxena, 2011). In South African nurseries, rhizome and culm cuttings are the main propagating techniques. However, several concerns include the difficulty of transporting the propagating material and the bulkiness of the material. This has initiated the development of *in vitro* propagation (micro propagating through tissue culture) to promote sustainable production to meet market demands (Amlani et al., 2017).

2.4.2 Sweet bamboo (*Dendrocalamus asper*)

Economic and environmental factors play an essential role in the extensive cultivation of bamboo throughout the world. For industries, the high return for bamboo plantations has changed perspectives, causing a switch from other products to bamboo cultivation. Among the most cultivated bamboo species on a commercial scale is *Dendrocalamus asper* (Schult.) Backer. This is a tropical sympodial bamboo species with a pachymorph rhizome (Figure 2-7), native to Southeast Asia and Indonesia (Chandramouli & Viswanath, 2012). It comprises various cultivars, which are important for the production of different products (Sujarwo et al., 2015). This species is used extensively for the reclamation of many previously abandoned agricultural lands. Lands previously cultivated with *Dendrocalamus asper* bamboo species are now protected and properly managed due to new industrial interest and high returns for growing the crop (Chandramouli & Viswanath, 2012).

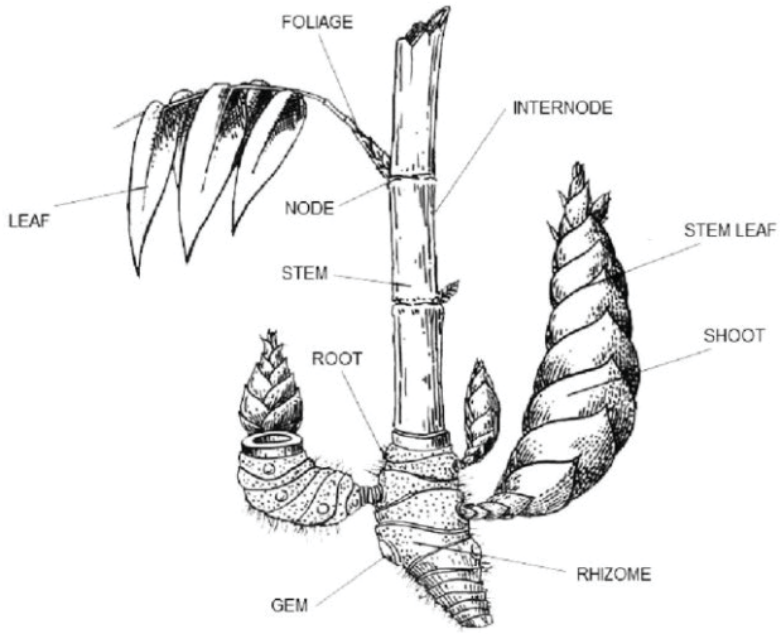


Figure 2-7: The pachymorph rhizome of the sweet bamboo (Lahr et al., 2015)

Sweet bamboo has been introduced to Africa and has been cultivated extensively in countries like Madagascar, the Democratic Republic of Congo, Kenya and Ghana. There is no information indicating its cultivation in South Africa. However, tropical regions in South Africa like northern KwaZulu-Natal, Limpopo and the Eastern Cape could have suitable climatic conditions for the cultivation of sweet bamboo.

Sweet bamboo is a species accepted worldwide as a source of nutritious food to numerous rural households (Singh et al., 2012). Its use in the food industry has increased in the past decades (Shroti et al., 2012), because of its high crude fibre content in fresh shoots. The fibre extracted from the fresh shoots has been used to enhance the fibre content of yoghurt, bread and cheese, and the manufacture of pasta products (Felisberto et al., 2017). These products are exported to international markets. Felisberto et al. (2017) have also shown that sweet bamboo's fresh culms constitute 16 g per 100 g of starch, 79 g per 100 g of fibre and less than 2% lipid content, making them a highly nutritious food source.

Sweet bamboo is cultivated for commercial purposes through rhizome and culm cuttings (Shroti et al., 2012). However, modern techniques are being developed, such as micropropagation using *in vitro* techniques (e.g. tissue culture, protoplast fusion and embryo rescue) (Shroti et al., 2012). These techniques are being used to optimise the level of production to meet the industrial demand.

However, it has currently been evaluated that the cultivation of rhizomes as a planting stock gives a much better yield and carbon biomass. For example, in a study by Sujarwo et al. (2015), it was concluded that rhizome propagation had a much better yield than culm propagation. An efficient propagating technique is essential, especially because bamboo's propagating material is difficult to handle and transport, and growth is slow using existing procedures. In addition, factors like soil conditions, rainfall, aspect and altitude are important factors for biomass accumulation (Chandramouli & Viswanath, 2012).

There are other species suitable for South Africa's sub-tropical environmental conditions, like *Bambusa bambos* and *Bambusa nutans,* which can be cultivated for large-scale commercial production. However, due to the little available information about the species' water use, mechanical properties and plant behaviour, various research projects are being developed to address these knowledge gaps.

2.4.3 Small-scale cultivated bamboo species in South Africa

Other species cultivated in South Africa are *Bambusa oldhamii,* commonly known as the giant timber bamboo, *Dendrocalamus hamiltonii* and Berg bamboo (Table 2-2). The latter is scientifically known as *Thamnocalamus tessellatus* and is endemic to South Africa and to the high mountains of Lesotho and Swaziland.

This species is the only African bamboo with the ability to grow in other parts of the world due to its hardiness. Apart from the Berg bamboo, each of the species mentioned above is commercially cultivated in South Africa, mostly in the Eastern Cape and KwaZulu-Natal. They are being grown for both industrial and ecological uses. Industrial uses include construction, paper and furniture, while ecologically they are grown for carbon sequestration, water quality and soil improvement.

Table 2-2: Alien bamboo species in South Africa and growing conditions in relation to adapted environments

Species name	Native	Growth form	Climate	Environmental conditions	Area adapted in SA
Emily van Rijswick sp.	Asia	Clumping	Tropical	Prefer poor soils	Eastern Cape (St. Albans)
Berg bamboo (*Thamnocalamus tesselatus*)	South Africa	Clumping	Temperate	Prefers river & cave edges Altitude 1200-2400 m	Drakensberg
Bambusa balcooa	Northern India	Clumping	Tropical	Heavy soils, 600 mm rainfall/year Altitude 700 m above sea level	Eastern Cape, Western Cape
Bambusa vulgaris	Unknown	Clumping	Tropical	Altitude 1000-1200 m	Across Africa
Dendrocalamus asper	Indonesia	Clumping	Subtropical, Tropical	Loamy, Black soils	PMB, DBN North Coast
Bambusa oldhamii	Taiwan (China)	Clumping	Tropical	Average water Clay, Loam & sand soils	
Dendrocalamus hamiltonii	Asia	Clumping	Subtropical, Tropical	Average water, Altitude 870-1800 m Well-drained loam soils	
Phyllostachys nigra	China	Runner	Temperate	Rich in nutrients topsoil	Cape Town

Acknowledgement
(https://www.brandsouthafrica.com/investments-immigration/economynews/bamboo-051211)
(https://www.arkive.org/berg-bamboo/thamnocalamus-tessellatus/)
(https://www.ecoplanetbamboo.za.com/)
(https://www.scribd.com/document/141583688/African-Bamboo-Species)
(http://www.brightfields.co.za/bamboo-plants-for-sale/)
(http://www.learn2grow.com/plants/bambusa-oldhamii/)
(http://nbm.nic.in/PDF/Manual_Bamboo_Plantations.pdf)
(http://plantinfo.co.za/plant/phyllostachys-nigra/)

2.5 BAMBOO MARKET IN SOUTH AFRICA

In recent years, most African countries, excluding South Africa, have engaged in working with the International Network for Bamboo and Rattan to develop the market, establish large-scale plantations and industrial processing to manufacture various bamboo products (Scheba et al., 2018). The bamboo industry and research in South Africa are still developing (Figure 2-8) with small exports to international markets. Most of the bamboo plantations, especially the giant bamboo, *Bambusa balcooa*, grow naturally in the Eastern Cape, and about 13 million tons are exported to industries in India and China for processing (Dunbar, 2018). The species is also economically important for paper and pulp manufacturing industries (Dunbar, 2018).

There are also various South African industries and societies that promote bamboo cultivation, and use the plants to manufacture various products to meet market demands (e.g. Bamboo Revolution is an industry that produces bamboo watches). It also has the potential to provide an environmentally friendly alternative to single-use plastic and polystyrene as the products of processed bamboo are 100% biodegradable (Nurul Fazita et al., 2016). In addition, bamboo products such as flooring, furniture, charcoal and plywood are increasing in popularity. The Eastern Cape Development Corporation is a society that promotes bamboo cultivation in South Africa.

The domestic market has the potential to increase in South Africa. For example, since bamboo plantations can be used to generate energy, industries that supply energy like Eskom can switch from the use of coal to a bamboo energy supply (Busani, 2011).

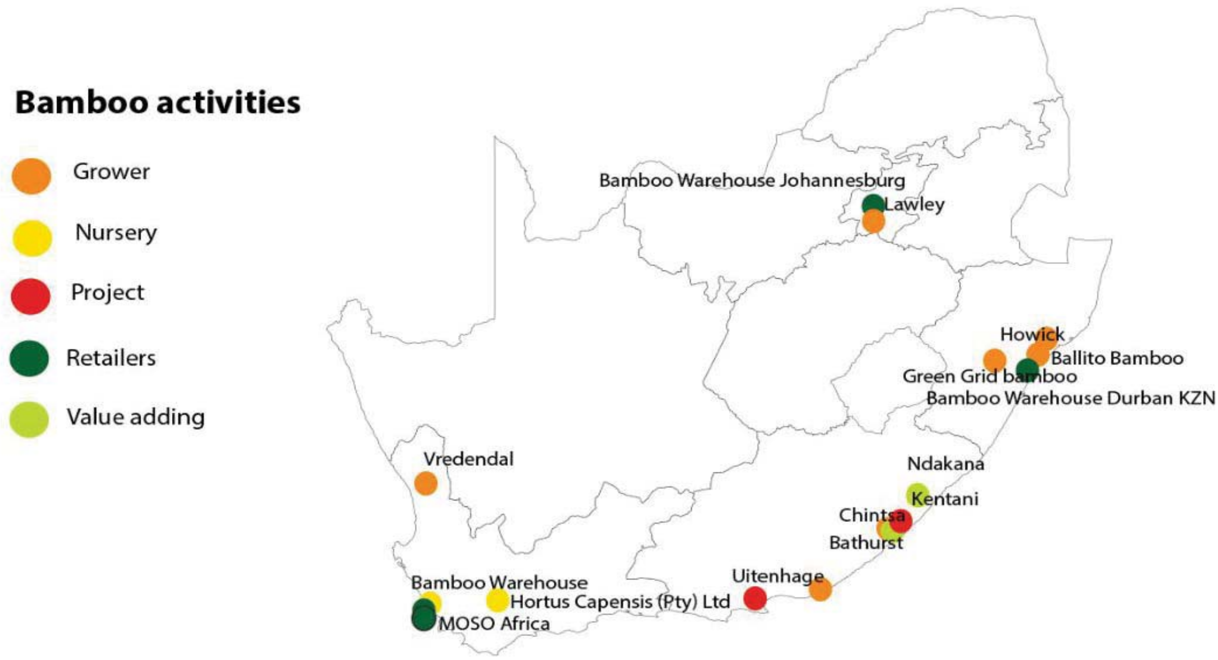


Figure 2-8: Bamboo activities in South Africa (Scheba et al., 2018)

2.6 WATER USE AND SAP FLOW QUANTIFYING TECHNIQUES

2.6.1 Understanding evapotranspiration and environmental effects

Water is essential for plant growth and development. Plants use water for metabolic activities and physiological processes. Therefore, soil moisture is absorbed by plants through fine roots, and it is translocated by the xylem tissue cells to leaves for photosynthesis and carbohydrate or sugar synthesis. Absorbed water can then be lost through stomatal openings in plant leaves (transpiration) due to changes in environmental conditions. Environmental conditions such as warm air temperatures, low relative humidity, soil moisture, wind and light play a crucial role in the rate of plant transpiration and soil evaporation (Figure 2-9). Therefore, quantifying the water use of different plant species in relation to the environmental and human effect are very important aspects in understanding the effect of biodiversity on water resources (Schmidt et al., 2009). Technological practices and techniques that measure and monitor plant water use are required to understand the use of available water. However, understanding and modelling the water use of different plant species has been a great challenge for decades.

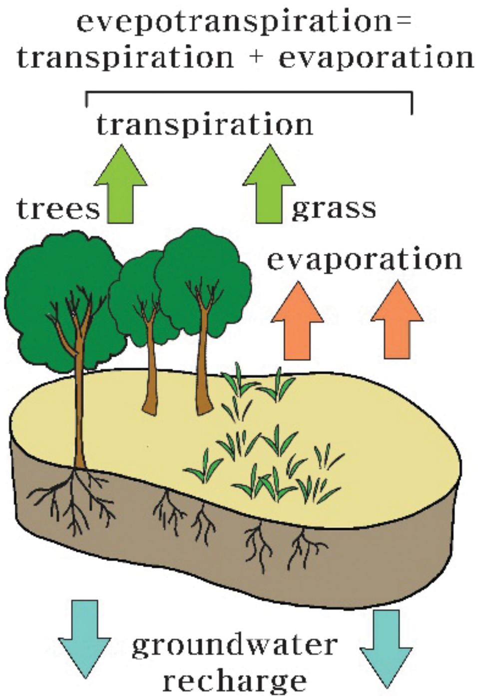


Figure 2-9: Schematic diagram for evapotranspiration (Muhammad, 2018)

Both indirect and direct methods have been used to measure the transpiration and water use of tree species. Indirect methods include the micrometeorological measurement of evapotranspiration, which can be used to estimate plant water use. An alternative approach is the indirect estimation of water use based on soil moisture balance calculations.

The major limitations of indirect methods may include factors such as soil type, time of measurement and prevailing meteorological conditions. Therefore, setting up an automatic weather station can be useful in data interpretation and referencing. However, water use can also be measured directly using stem steady state and heat pulse velocity methods that measure the sap flux density passing through a point in a stem.

2.6.2 The effect of bamboo structure on water use

The fast growth rate of bamboo species necessitates research on its potential impact on South Africa's scarce water resources. Transpiration rate and evapotranspiration are essential components to assess their potential effect on water resources. These components affect the available water yield and through the catchment water balance. Therefore, various studies have been conducted to understand the effect of different forest species on the local water cycle (Tsuruta et al., 2016). However, there is very limited information regarding the water use of commercial bamboo species on the local water cycle. Since bamboo is a monocotyledonous grass and hollow within the stem structure (Figure 2-10), the vascular tissue arrangement differs from that of other forest species. Metaxylem (Mx) and phloem (P) tissues are not uniform and are located within fibre caps at the inner and outer part of the culm wall (Wang et al., 2012). This makes it difficult to quantify water use using standard approaches.

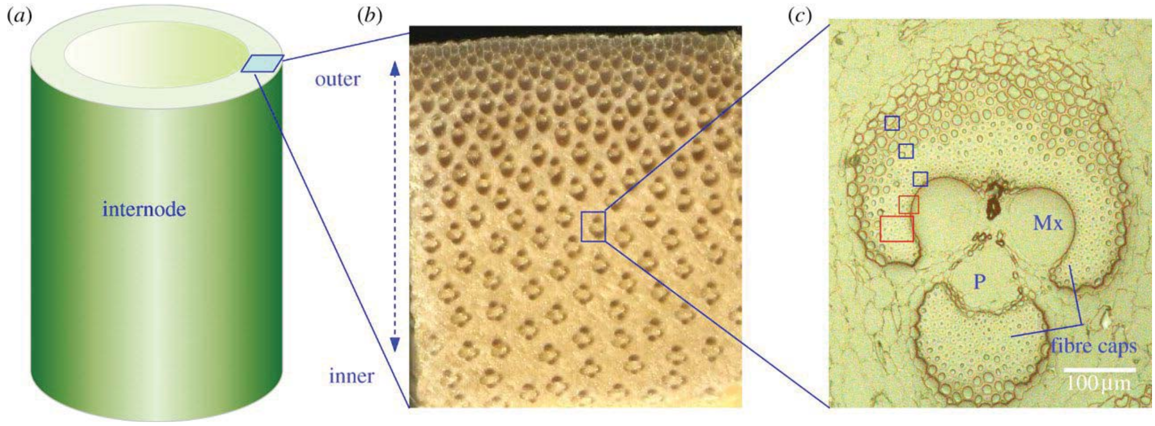


Figure 2-10: Cross-section of *Phyllostachys pubescens* bamboo species and vascular bundle arrangement (Wang et al., 2012)

However, the expansion of bamboo plantations is predicted to have an impact on water resources in the country, due to their reported high growth rates. Water resource managers are concerned about the threat that bamboo expansion will have on South Africa's water security. This is especially true for invasive monopodial bamboo species because of their high potential to aggressively spread, forming dense culms and thin rhizomes that extend horizontally under the soil surface over long distances to water sources (Tsuruta et al., 2016).

Sympodial species, with their dense and numerous leaf structures, may also be high water users. In addition, the continuous rise in temperature due to global warming will increase transpiration. Transpiration in various species is a process that has been globally used to measure the amount of water uptake by different plant species and to evaluate their effect on the terrestrial water cycle (Laplace et al., 2017). It has been reported that bamboo species have higher transpiration rates compared with other forest species (Laplace et al., 2017). However, the quantity of water used by bamboo plants differs among species. Factors like culm age, rhizome architecture (Tsuruta et al., 2016), vapour pressure deficit (VPD), culm diameter (Tsuruta et al., 2016), and soil properties (thermodynamic potential) in relation to bamboo's high root pressure (Yang et al., 2015) are factors that can affect water uptake and subsequently transpiration.

The culm of bamboo is characterised by vascular bundles that lack secondary growth and do not regenerate after sprouting (Tsuruta et al., 2016; Yang et al., 2015). This characteristic promotes a high water uptake by the roots to supply the transpiration system of the plant during the day. A mature bamboo plantation has been estimated to use on average 3 285 mm of water annually (Table 2-3) (Kleinhenz & Midmore, 2000). Various sap flow measuring techniques are used to measure the amount of water utilised by different plant species for growth and development.

Table 2-3: The estimated water use of mature bamboo species (Kleinhenz & Midmore, 2000)

Parameter	Value	Unit	Source
Leaf biomass (dry)	5	[t] [ha]$^{-1}$	overseas literature
Leaf dry/fresh weight	10	[%]	own measurements
Leaf biomass (fresh)	0.5	[t] [ha]$^{-1}$	own calculation
Specific leaf area	150	[cm leaf area]^{2} [g dry leaf]$^{-1}$	overseas literature
Specific leaf area	15	[cm leaf area]^{2} [g fresh leaf]$^{-1}$	own calculation
Leaf area index	7.5	[m leaf area]^{2} [m soil surface]$^{-2}$	own calculation
Transpiration rate	2.3	[mmol water] [m leaf area]$^{-2}$ [s]$^{-1}$	own measurements
Transpiration rate [a]	0.04	[ml water] [m leaf area]$^{-2}$ [s]$^{-1}$	own calculation
Water usage [b]	13	[l water] [m soil surface]$^{-2}$ [day]$^{-1}$	own calculation
Water usage [c]	9	[l water] [m soil surface]$^{-2}$ [day]$^{-1}$	own estimation
Water usage	3,285	[mm water]^{1}	own calculation

[a] Atomic weight of H_2O: 0.018 [g] [mmol]$^{-1}$
[b] ie Water usage at maximum transpiration rate for 12 [h] [day]$^{-1}$
[c] ie Water usage at estimated average yearly transpiration rate

2.6.3 Measuring bamboo water use

2.6.3.1 Granier's thermal dissipation probe (TDP)

The thermal dissipation method is a continuous sap flow measuring technique that has been intensively used in forest hydrology to measure the amount of water a plant species utilises (Lu et al., 2004). It is used to estimate the stand-scale transpiration of sampled trees to estimate forest water use. The method has been adopted globally due to its low costs, reliability and high degree of accuracy (Yang et al., 2015). For example, a study by Lu and Chacko (1998) indicated that this technique had a high level of accuracy when applied to young mango trees in Australia.

The technique has also been designed to accommodate daily sap flow measurements to compare the amount of water utilised by the plant in relation to environmental conditions. These are important features in understanding the flow of water moving from the soil to the plant roots, water transportation within the vascular tissues and transpiration at the leaf surface, i.e. the soil-plant-atmosphere system (Burgess et al., 1998). Sap flux density is also highly dependent on the vapour pressure deficit of the atmosphere (Yang et al., 2015). However, bamboo culm structure and anatomy have proven to be the limiting factors for the efficiency of the system in bamboo water use (Laplace et al., 2017).

The TDP system has been regarded as a sensitive sap flow system that can easily sense changes in sap flux density. This can be due to girdling, excision or defoliation (Lu & Chacko, 1998). Although sap flow techniques have been used extensively in temperate bamboo species, especially those with thicker culm structures, little work has been done on tropical bamboo species to measure their transpiration rates (Laplace et al., 2017). Even though not much work has been done on tropical bamboo species, some research has applied technical instruments like the stem steady state heat balance gauge, heat pulse method and stem tissue heat balance system to various plant species to measure their transpiration rates.

2.6.3.2 Stem steady state (SSS)

A stem steady state energy balance system is another alternative sap flow measuring technique that involves the application of continuous heat energy all around the tree trunk (Figure 2-11) through a heater and intact sensors to the tree stem (Vellame et al., 2010).

Lascano et al. (2016) indicated that the system has been modified from a wire intensive system to a less intensive wiring system, which has a flexible heater and improved thermal contact between temperature probes and the tree trunk. The latter system (Figure 2-12) consists of a heater, thermocouples and insulators, and can also be used on species with smaller diameters (Lascano et al., 2016). The method involves measuring temperature differentials by two temperature sensors at different tree stem points to calculate the sap flow rate through the following equation:

$$F = [\frac{P-(K_{st} \text{ x A x} \left(\frac{dT_u + dT_d}{d_x}\right) - K_{st} \text{ x } E}{C_p \text{ x } (T_u - T_d)}]$$

Equation 2-1: Sap flow rate equation for stem steady state

Where F is the sap flux (kg s^{-1}), P is the power of heater (V), K_{st} a thermal conductivity of stem (W m^{-1} ^oC), A is the cross-sectional area of the stem (m^2), [(dT_u + dT_d)/d_x] are measured temperature gradients (^{o} C m^{-1}) above and below heater, K is the sheath conductance (W V^{-1}), E is the output of thermopile, C_p is the volumetric heat capacity of water (J kg^{-1} ^oC) and (T_u – T_d) are mean temperatures of flowing sap into and out of the system (^oC).

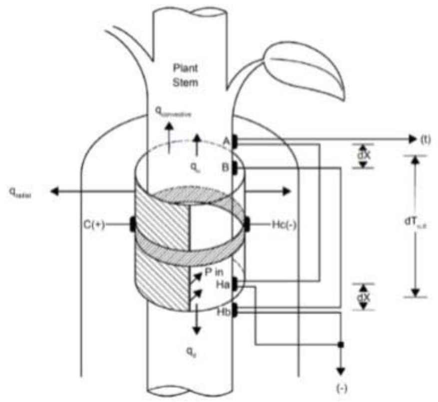


Figure 2-11: Schematic diagram of the former stem flow sensor (Lascano et al., 2016)

$$F = [\frac{p - q_c}{c_p}] \text{ x } dT$$

Equation 2-2: Equation used to measure sap flux for stem steady state

Where F is the sap flux (kg s^{-1}), P is the power of heater (V), q_c is convective heat flux (W), Cp is the volumetric heat capacity of water (J kg^{-1} $^oC^{-1}$) and dT is the average temperature measured with two thermocouples (^oC).

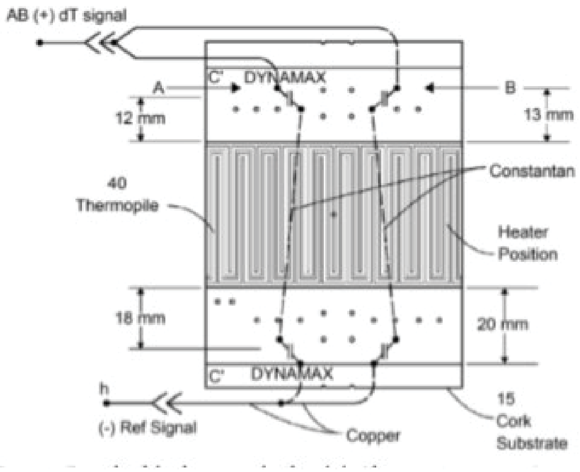


Figure 2-12: Schematic diagram of EXO-SkinTM Sap flow Model SGEX-13 (Dynamax Inc., Houston, TX) (Lascano et al., 2016)

Measurements can be done under a steady state condition by insulating a small stem portion and the intact sensors from the external temperature (Savage et al., 1993). The water use of mature bamboo culms can also be estimated if total leaf biomass and specific leaf area are known. These values can be used to calculate the total leaf area and, subsequently, transpiration rate, which are important parameters for estimating water use (Kleinhenz & Midmore, 2000).

2.6.3.3 Heat ratio method (HRM) or heat pulse velocity (HPV)

The heat ratio method is a heat pulse velocity technique used to measure sap flow. This technique has been successfully used worldwide to quantify water use for different woody plant species and has been extensively used by researchers in South Africa (Gush, 2008). The technique uses a thermometric device to measure the sap flow rates or water use of woody plant species. The device is based on a three-probe configuration and is characterised by two temperature probes (downstream and upstream) that are inserted at an equal distance from a heater probe that discharges a short pulse of heat (Figure 2-13).

The heat acts as a tracer and is used to measure the ratio of the downstream to upstream probe every 60 seconds following a heat pulse from the heater. This is used to calculate sap velocity (Burgess et al., 2001).

The HRM system was first proposed by Marshall (1958) to calculate heat velocity (V_h) in larger plants, such as forest species, whereas Hogg et al. (1997) developed it to calculate the sap velocity (S) of smaller plants. The heat pulse velocity (V_h) is then calculated from Burgess et al. (2001):

$$V_h = \frac{k}{x} \ln\left(\frac{V_1}{V_2}\right) 3600$$

Equation 2-3: Burgess et al. (2001)'s equation for calculating sap flow in heat pulse velocity

Where V_h is the heat velocity (cm hr^{-1}), K is the thermal diffusivity of fresh wood, x is the distance of each temperature probe from the heater probe (cm), and V_1 and V_2 are temperature increases in the upstream and downstream probes (^oC) at equidistant points.

The sap flow velocity is based on the following equation based on Hogg et al. (1997):

$$S = \frac{K_{cw} \ln(\frac{T_u}{T_l})}{X C_{pw} P_w}$$

Equation 2-4: Equation for calculating the sap flow velocity of heat pulse velocity

Where S is the sap velocity (cm hr^{-1}), K_{cw} is the thermal conductance, C_w is the specific heat of the sap (4 180 J kg^{-1} $^oC^{-1}$) and T_u and T_l are the temperature rises in the upstream and downstream probes (^oC).

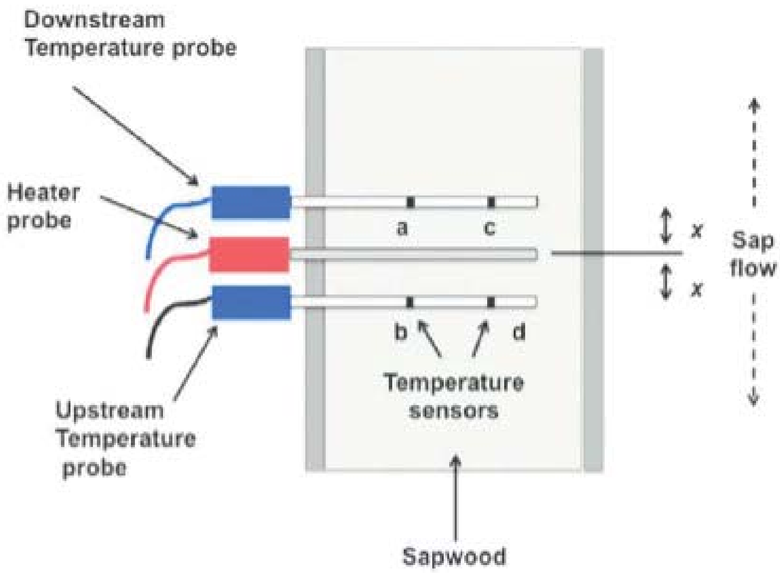


Figure 2-13:Schematic diagram of the heat ratio method (Bayona-Rodríguez & Romero, 2016)

2.7 BAMBOO SAP FLOW MEASURING CHALLENGES AND LIMITATIONS

The above thermoelectric technologies have been successfully used in dicotyledonous stems, which have a pith at the centre of the stem surrounded by vascular bundles. One of the challenges of determining the water use of bamboo is that it is a monocotyledonous grass species that has stems with scattered vascular bundles near the outside edge of the stem, and no pith region. These vascular bundles lack secondary growth and do not regenerate after sprouting (Tsuruta et al., 2016; Yang et al., 2015). This characteristic promotes a high amount of water uptake by the roots to supply the transpiration system of the plant during the day. By contrast, dicotyledonous stems have their vascular bundles in a ring arrangement. Therefore, the heat pulse and steady state technologies that have been successfully developed to measure the water use of dicotyledonous tree species may not be suitable for bamboo species.

Other factors that need to be taken into account when measuring the water use of bamboo are culm age and diameter (Tsuruta et al., 2016), and soil properties (Yang et al., 2015), which can affect the water uptake and transpiration. Since the heat ratio technique quantifies sap flow with respect to the depth of the temperature probes in a stem, it is necessary to determine the diameter of each culm in a bamboo clump with respect to the conducting area (xylem).

2.8 CONCLUSION

There is still a gap in understanding the relationship between various bamboo species and the hydrological cycle, and how these components affect the quantity and quality of available water. This is particularly so in South Africa where bamboo water use has not been determined before. Therefore, understanding this relationship is crucial for optimising water resources in a drought-prone country like South Africa.

CHAPTER 3: STUDY SITES

3.1 KWAZULU-NATAL

The bamboo study site selected in KwaZulu-Natal was Shooter's Hill farm. The farm belongs to Mr Guy Solomon, who started a pilot bamboo project in 2008. Approximately 10 ha has been planted to at least 15 different bamboo species (Plate 3-1). The site is located near Otto's Bluff in the uMgungundlovu District Municipality, KwaZulu-Natal, South Africa. The farm is approximately 980 m above sea level. Mr Solomon's bamboo business comprises a bamboo nursery, a mechanical operations area that processes harvested bamboo and five sites that have been planted to bamboo.

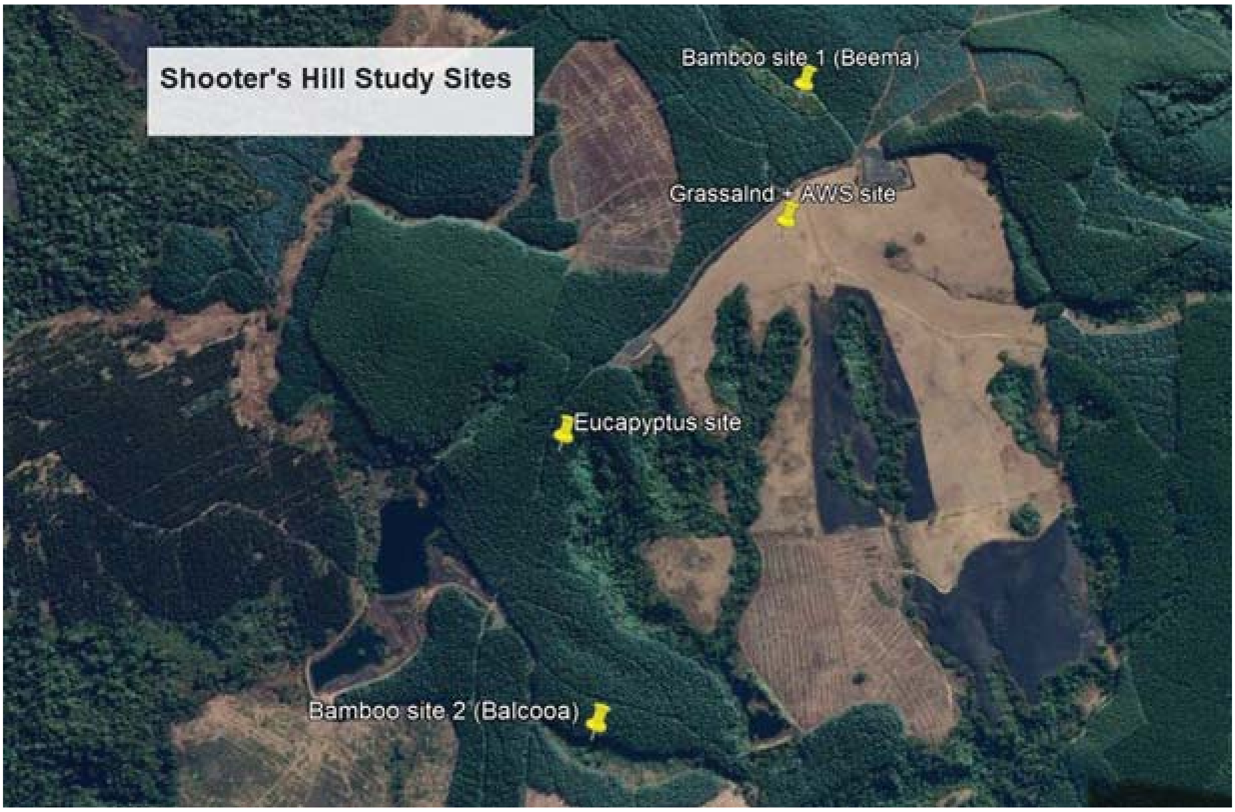


Plate 3-1: KwaZulu-Natal study site at Shooter's Hill farm

3.1.1 The nursery

The nursery comprised numerous bamboo species propagated in pots (Plate 3-2). Most of the species had been accessed through the National Bamboo Association of South Africa. However, some species had been imported from overseas (India).

Plate 3-2: Nursery of different bamboo species

3.1.2 Harvesting operations area

After the bamboo poles (culms) have been harvested, they are transported to the operations area where they are processed. This includes soaking the poles in boric acid (borax) to prevent insect and fungal damage. The mature bamboo poles or culms are then cut into slats using a mechanical saw (Plate 3-3). The operation of this machine requires skill to line up the poles for cutting and to feed the poles through a metal splitter, which splits the pole into slats. The slats are then stored according to size (Plate 3-4) before they are transported.

Plate 3-3: Mechanical saw for splitting bamboo poles

Plate 3-4: Bamboo poles and slats ready for marketing

3.1.3 Site 1

This site is extensive and is situated next to a wattle plantation (Plate 3-5) and open grassland. The security of the site was considered to be good. It comprised a wide variety of species:

- *Bambusa balcooa* variety beema (beema bamboo) was obtained from Dr Barathi of GrowMore Biotech for charcoal production to power electricity. The ideal interplant spacing is 3 m. At thinning, Mr Solomon keeps six main stems and harvests the culms every three and a half years. It can withstand temperatures of -1 °C.
- *Dendrocalamus asper* (giant bamboo) is an evergreen, dense-clumping species growing to 15 m. Mr Solomon reported that it is a soft bamboo that has not frosted on the farm despite temperatures of -4 °C. Mr Solomon has planted 2 to 3 ha of this species.
- *Bambusa bambos* (giant thorny bamboo) has spines that make it a good species for security fencing. Mr Solomon has planted about 4 ha of this species. He harvests the poles every three years.
- *Chusquea mimosa* (mimosa bamboo) has very small yellow leaves. Mr Solomon puts his cattle to graze in this stand of bamboo as the leaves and young shoots are edible.
- *Vivax aureocaulis* (gold vivax) is a giant bamboo with a yellow and green striped culm. Although people are concerned about the invasiveness of bamboo, this species has not spread since it was planted on the farm 10 years ago.
- *Phyllostachys nigra* (black bamboo) grows up to 5 m. The culms turn black after two or three seasons.
- *Bambusa tuldoides* (punting pole bamboo) grows to a height of 17 m. The culm has a small hole that must be taken into account if this species is selected to measure its water use. The species is cold tolerant.
- *Phyllostachys aurea* (golden bamboo) has the potential to be aggressive as it spreads through runners. The culms grow close together. It is popular for its edible shoots.
- *Bambusa oldhamii* (giant timber bamboo) is a fast-growing bamboo that is frost tolerant. It is suitable for windbreaks and has edible shoots.

Plate 3-5: Bamboo at Site 1 next to a wattle plantation

3.1.4 Site 2

This site was narrow and had the only African bamboo that occurs in South Africa growing on it. The species is called *Oxytenanthera abyssinica,* also known as abyssinica bamboo, and produces lots of mulch (Plate 3-6). It has an open, clumping growth habit and produces fine leaves that are used for fodder. Although flowering typically occurs after long periods of growth (seven to 21 years), flowering of this species was observed at this site (Plate 3-7).

Bambusa balcooa, commonly known as balcooa, was the key species at this site. Mr Solomon reported that, although most bamboo species die after flowering, this was not the case with balcooa. It is a fast-growing, clumping bamboo that does not need replanting. This species is commonly grown in the Western Cape.

Plate 3-6: *Oxytenanthera abyssinica*, the African bamboo growing at Site 2, which produces lots of mulch

Plate 3-7: *Abyssinica bamboo* in flower

3.1.5 Site 3

This was an old gum plantation that had been planted to different bamboo species. Mr Solomon reported that *Bambusa bambos* was first planted there approximately 10 years ago. However, he would not plant it again as it is very difficult to harvest. By contrast, *Dendrocalamus asper*, which was planted there five years ago, is easy to manage. The shoots are currently ready to harvest. This must be taken into account if the species is selected for in-depth water use studies. Other species planted at this site were:

a) *Bambusa bema:* a very high-yielding species with narrow green leaves.
b) *Dendrocalamus hamiltonii,* a tall bamboo with drooping tops that grows up to 20 m. Its growth habit is clumping with a few closely growing culms.
c) *Bambusa vulgaris,* also known as the common bamboo. It is another clumping bamboo species with a yellow and green striped culm. Numerous large shoots were observed growing from the base of the clump.

Mr Solomon explained that bamboo plants have a very high growth rate and can reach their maximum height in a single growing season. In each successive year, new shoots are produced from the base of the plant. They do not increase in diameter during that year, but in subsequent years they lignify and increase in strength and density. In each successive year, the new shoots get bigger so that the shoots produced in Year 4 will have a greater diameter than those produced in Year 1. Bamboo is therefore a very sustainable resource as the culms can be harvested every two to three years and it does not need to be replanted after harvest.

3.1.6 Site 4

This site was an old sugar cane land that had been planted to *Bambusa beema* (Plate 3-8). The plants are currently four years old, and harvesting has commenced. Mr Solomon noted that this is a key species as it grows well, has a very high growth rate and is easy to manage.

Plate 3-8: Four-year-old *Bambusa beema* showing high yields

3.1.7 Site 5

Bambusa tuldoides had been planted at this site, but it had been affected by the drought. Other species planted here included *Dendrocalamus asper* and *Bambusa multiplex*, a short (4.5 m) garden bamboo that forms tight clumps and is suitable for hedges. Another species propagated at this site is *Guadua angustifolia*, a thorny, clumping bamboo from South America (Plate 3-9). It is a popular species for building material due to its strength.

Plate 3-9 The spines of *Guadua angustifolia* make this species good for security hedges

3.1.8 Summary

The farm was ideal for the study due to a number of factors:

- The long history of planting in KwaZulu-Natal, South Africa (up to 10 years)
- The wide variety of species (at least 15)
- The large area planted (10 ha in total)
- The support of the farmer, Mr Solomon

After consideration of the characteristics of the five sites, Site 1 was selected as the most suitable site to study the water use of *Bambusa balcooa* variety beema and Site 2 was selected to study *Bambusa balcooa* variety balcooa.

3.2 EASTERN CAPE

The site with the most potential for the bamboo research study in the Eastern Cape was a commercial bamboo plantation established by EcoPlanet Bamboo Southern Africa, a subsidiary of an international company, the EcoPlanet Bamboo Group. The company, which is based in America, owns and operates the Kowie Bamboo Farm in the Bathurst area of the Eastern Cape. The farmland covers 482 ha, 72% of which has been planted to bamboo (Plate 3-10). The other 28% of the farm has been set aside for biodiversity and conservation purposes. Permission was obtained from the founding director of the company for the project team to measure the water use at this site, which is the largest commercial bamboo plantation in South Africa. A team visit to the site confirmed that it had potential for larger scale micrometeorological measurements. EcoPlanet represents a totally different climate to KwaZulu-Natal. Combined with the fact that it only grows bamboo on reclaimed degraded farming land makes it an ideal study site.

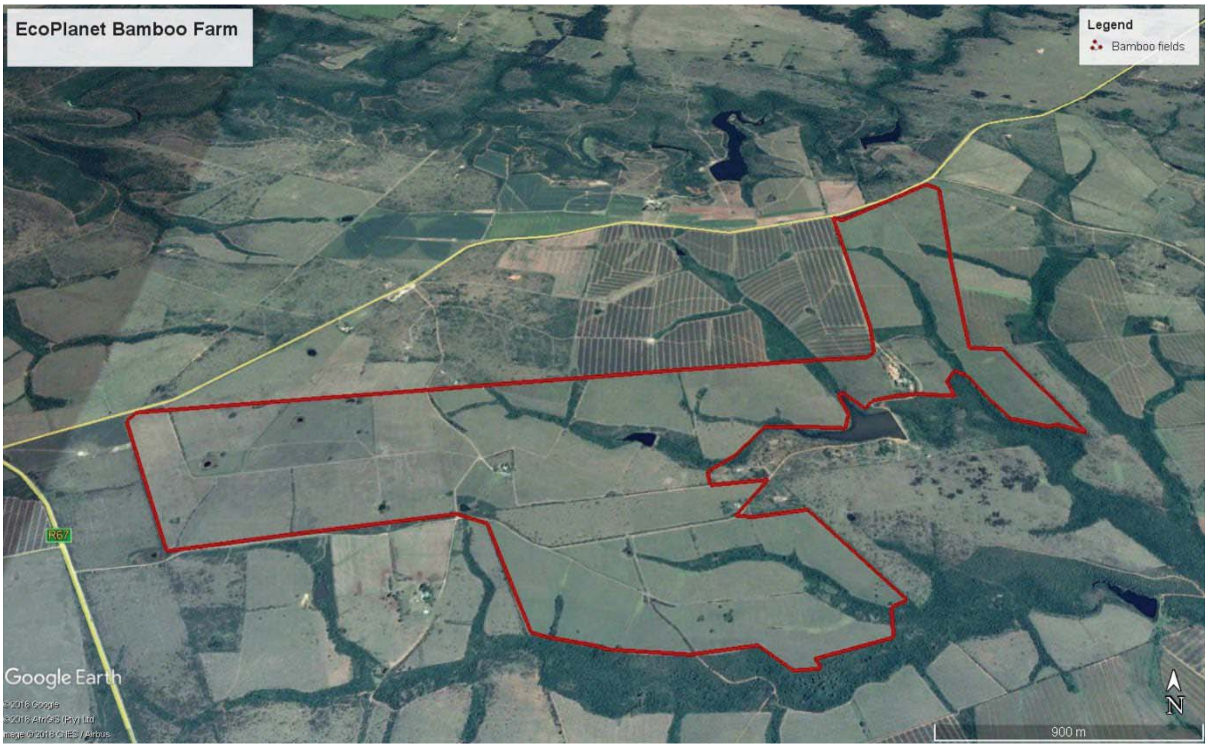


Plate 3-10: Study site in the Eastern Cape

EcoPlanet Bamboo is certified with the Forest Stewardship Council, which ensures the responsible supply of timber from well-managed bamboo plantations that provide environmental, social and economic benefits (EcoPlanet Bamboo, 2018). South Africa – through EcoPlanet – is one of only two countries in the world to have met this international forestry sustainability standard for commercial bamboo plantations. Two species of bamboo that have been naturalised in South Africa, *Bambusa balcooa* and *Oxytenanthera abyssinica*, have been established as commercial plantations at Bathurst (Plate 3-11). Some of the products that are produced from these plantations include 100% natural charcoal air purifiers and water filters at Pick n Pay, its 100% chemical-free bamboo charcoal soap range at Nature's Way and the entire range at Leach Pharmacy (EcoPlanet Bamboo, 2018).

Plate 3-11 Bamboo plantation at EcoPlanet Bamboo farm

One of the challenges that EcoPlanet has faced is obtaining reproductive material of the different bamboo species. Most species of bamboo only produce seeds after 10 to 60 years of growth, depending on the species (SF Gate's Home Guides, 2018). Since the majority of bamboo plants only flower once in their lifetime and die after flowering, access to bamboo seeds is rare.

Commercial bamboo growers usually propagate new plants by taking vegetative cuttings, rather than waiting for maturation and seed production. Many species of bamboo produce underground stems called rhizomes or runners. These rhizomes can be cut into segments that can be transplanted to provide a quick alternative to seed germination. Digging up clumping bamboos and dividing the underground rhizomes, as well as taking branch and culm cuttings, also provides methods of obtaining additional plants from a single specimen. However, a knowledge of the genetic background of the cuttings is critical as the longevity of the plant is carried in the genetic material. Thus, if cuttings are collected from already old material, the plants may all die in a shorter than expected period, resulting in crop failure.

EcoPlanet Bamboo has also successfully propagated bamboo through tissue culture. The plantlets produced through tissue culture are not genetically modified, but they are grown from the cells of the parent plants in a laboratory. This innovative means of propagating *Bambusa balcooa* was initiated in the Eastern Cape for a number of reasons (EcoPlant Bamboo, 2018):

- *Bambusa balcooa*, is naturalized in South Africa and occurs and thrives across the Eastern Cape.
- The area meets the stringent land selection criteria required by the Forest Stewardship Council.
- The land has been farmed for long periods of time under chemical systems.
- The area provides opportunities to provide work to communities that are unemployed.

3.2.1 Climate

EcoPlanet is characterised by an equable climate with few extremes of temperature and ample precipitation in all months. The Köppen Climate Classification subtype for this climate is Cfb (marine West Coast climate). The average temperature for the year at this site is 16.7 °C. The warmest month is January, with an average temperature of 20.6 °C. The coolest month is June, with an average temperature of 15 °C. The average amount of precipitation for the year in Bathurst is 696 mm. The month with the most precipitation on average is March with 78.7 mm. The month with the least precipitation is June with an average of 33 mm.

3.2.2 Summary

The Eastern Cape EcoPlanet site had high potential for the Eastern Cape research site for the following reasons:

- It represented the major growing area targeted by the Eastern Cape's Industrial Development Corporation for rural upliftment.
- It is the largest commercial bamboo operation in South Africa.
- It represented the marginal rainfall climate of South Africa with all year-round rainfall. The climate has been identified as suitable for growing bamboo.
- The site was suitable for micrometeorological techniques.
- EcoPlanet was prepared to collaborate with the project team.

CHAPTER 4: MATERIALS AND METHODS

4.1 METEOROLOGICAL STATION

4.1.1 Automatic weather station in KwaZulu-Natal

Meteorological data is required as input for calculations to determine total evapotranspiration and interpret sap flow data (Allen et al., 1998). This data was obtained from the automatic weather station (AWS), which was installed at a nearby grassland site in August 2018 (Plate 4-1a). The AWS was placed on a flat uniform grassland area to meet the requirements of the FAO 56 reference evaporation (ET_0) calculations (Allen et al., 1998). A Campbell Scientific CR1000 datalogger recorded the air temperature (CS500, Vaisala Inc., Helsinki, Finland), the relative humidity (CS500, Vaisala Inc., Helsinki, Finland), the wind speed and direction (Model 03002, R.M. Young, Traverse City, Michigan, USA), the solar radiation (Kipp and Zonen CMP3) at 2 m, and the rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) at 1.2 m. Data from the station was downloaded at hourly intervals to the logger linked via a modem to the University of KwaZulu-Natal's AIM server (Perdrial et al., 2020).

4.1.2 Installation of an AWS at the EcoPlanet Bamboo farm

A 9 m lattice mast was erected in the centre of the bamboo plantation to provide weather variables for the Eastern Cape experiments (Plate 4-1b). The AWS was installed at EcoPlanet Bamboo in February 2019. The weather instruments used were identical to those used at Shooter's Hill, but they were installed 9 m above ground level. Due to the remote nature of the Eastern Cape site from the project team base in Pietermaritzburg, it was not feasible to visit the site weekly to download the data. Cell phone communication was therefore set up to download the data every 30 minutes. Key variables were displayed graphically for easy confirmation that the equipment was working. Battery voltage was also recorded.

(a) (b)

Plate 4-1: Automatic weather station at the grassland site KwaZulu-Natal (a) and the 9 m lattice mast with the AWS in the Eastern Cape (b)

4.2 VOLUMETRIC WATER CONTENT

Soil water content probes were placed at each site to measure the hourly volumetric water content (VWC). These measurements coincided with the hourly sap flow measurements of the HPV and Dynamax systems.

At each site, a pit was opened and three Campbell Scientific CS 616 TDR probes, connected to channels on the CR1000 data logger, were inserted horizontally at 0.2, 0.4 and 0.7 m to ensure that the soil water profile was monitored (Plate 4-2). These consisted of two 0.3 m-long stainless steel rods (wave guides) and electronics designed to measure the water content using the time domain frequency technique with a CR1000 datalogger (Kelleners et al., 2005). The probes were positioned to measure the total profile water content from the surface to a depth of 0.8 m.

Plate 4-2: Installed soil water probes (CS 616) for measuring soil water

The total profile water content (equivalent depth of water) was calculated using the sum of the volumetric water content measured at each depth multiplied by the depth of the soil profile to quantify the depth of water within the root zone:

$$W_{rz} = \theta_{v1}d_1 + \theta_{v2}d_2 + \theta_{v3}d_3$$

Equation 4-1: Total profile water content equation

Where W_{rz} is the total profile water content in the root zone, θ_{v1}, θ_{v2} and θ_{v3} are volumetric water contents, and d_1, d_2 and d_3 are the three soil depths represented by each probe (Evett et al., 2006).

4.3 EXPERIMENTAL DESIGN

At each site, a 10 m x 10 m plot was marked out to include representative plants and avoid potential edge effects (Figure 4-1). To quantify (scale-up) the water use of these multiple stemmed species, it was necessary to measure the diameter of each culm of each clump. Vernier callipers were used to record the diameter of each of the culms of each bamboo clump (Plate 4-3).

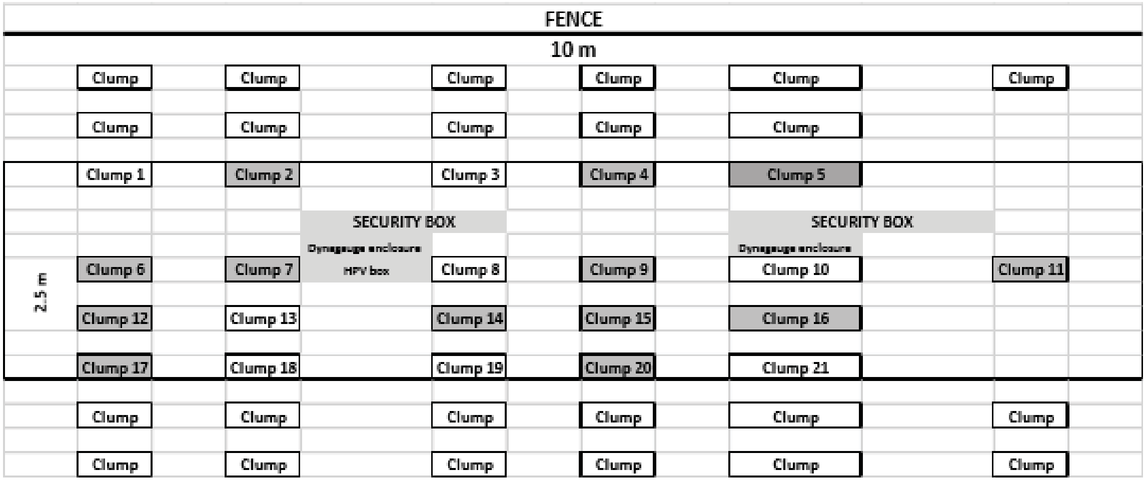


Figure 4-1: Example of the site layout of bamboo clumps and equipment at the Beema site, Shooter's Hill

Plate 4-3: Measuring the culm diameters in the 10 x 10 m study plot with Vernier callipers

4.3.1 Bamboo culms, eucalyptus and wattle tree growth monitoring

Bamboo is recognised to have a very quick growth rate and is therefore being promoted in South Africa to address the problem of fuel shortage, deforestation and sustainable timber, and as part of rural agricultural development (Gupta and Kumar, 2008). However, little information is available on the growth characteristics of the different species grown under different climatic conditions in South Africa. The aim of the growth study experiments was to determine the growth of balcooa and beema at Shooter's Hill in KwaZulu-Natal and of balcooa in the Eastern Cape. In KwaZulu-Natal, similar data from the adjacent eucalyptus and black wattle trees was also taken to provide comparative data of the different land uses in the study.

4.3.1.1 Growth of *Bambusa balcooa* var. beema (KwaZulu-Natal)

At the beema study site, 21 bamboo clumps in a 10 x 10 m plot were included in the growth study. A total of 251 culms were tagged and the diameter at breast height (DBH) was measured with Vernier callipers. Measurements were taken at the start of the study on 13 August 2018, and at the end of the study on 3 February 2020 (Plate 4-3).

The selected balcooa study site had one clump within a 3 x 2 m plot and 72 bamboo culms. This was used for the growth study. Bamboo culms were measured at the beginning of the study using Vernier callipers on 24 August 2018 and at the end of the study on 26 February 2020.

4.3.1.2 Growth of eucalyptus and wattle

The diameters of four selected eucalyptus trees were recorded at the start of the study. Monthly stem diameter measurements were subsequently taken. This was important in understanding the rate of tree growth and in predicting the growth of the heartwood to calculate the sapwood area for the HPV water use measurements. The measurements were taken at the tree section where probes were installed. A similar approach was applied to the wattle trees.

4.3.1.3 Growth of *Bambusa balcooa* var. beema (Eastern Cape)

At the Eastern Cape site, six bamboo clumps were tagged and measured on 7 February 2019, 14 May 2019, 12 November 2019 and 8 August 2020. The diameter at breast height of 76 culms was measured.

4.3.2 Leaf Area Index

Using a LI-COR LAI 2200 plant canopy analyser, Leaf Area Index (LAI) measurements were collected from the balcooa, beema, eucalyptus and wattle sites. This provided an understanding of growth with respect to canopy cover and was an important variable regarding plant water-use (Jordan, 1969). A 10^{o} view cap was used in measuring the LAI data.

In KwaZulu-Natal, monthly measurements were performed to estimate the LAI from April 2019 to February 2020. However, owing to a calibration problem with the analyser, only the values from April to September 2019 are shown. The procedure involved taking one clear sky reading (the "above" measurement) and four below-canopy measurements ("below" canopy) in a sequence programmed to give four replications per LAI measurement.

4.4 BAMBOO ANATOMY

4.4.1 Sample and blocks' preparation

Several 1 mm^2 sections were cut from the wall of selected bamboo culms harvested at Shooter's Hill, KwaZulu-Natal (Plate 4-4). The samples were then fixed in 3% glutaraldehyde overnight to preserve quality and inhibit desiccation. A 0.05 M sodium cacodylate buffer was then used to wash the sample thoroughly by immersing it twice for 30 minutes. The samples were fixed with 2% osmium tetroxide (7:3 ratio of 2% osmium tetroxide and 0.05 M sodium cacodylate buffer) and left overnight. Samples were then washed in a 0.05 M sodium cacodylate buffer sample by immersing them twice for 30 minutes.

The sodium cacodylate was then extracted using a Pasteur pipette, and samples were dehydrated with 30% ethanol for 20 minutes, and then left overnight in 50% ethanol. The 50% ethanol was extracted using a Pasteur pipette, and samples were dehydrated with 70% ethanol for 10 minutes, 90% ethanol for 15 minutes, and 100% ethanol twice for 15 minutes each time, 100% propylene oxide for 15 minutes subsequently and 100% propylene overnight. Propylene was then extracted using a Pasteur pipette and samples were immersed in a 1:1 Spurr's resin (a low-viscosity hydrophobic resin that contributes to its penetration in plant tissue) and propylene oxide for 60 minutes. Samples were immersed in 100% Spurr's resin twice for 120 minutes. Samples were put in an oven and cured at 60–70 °C for 24 hours.

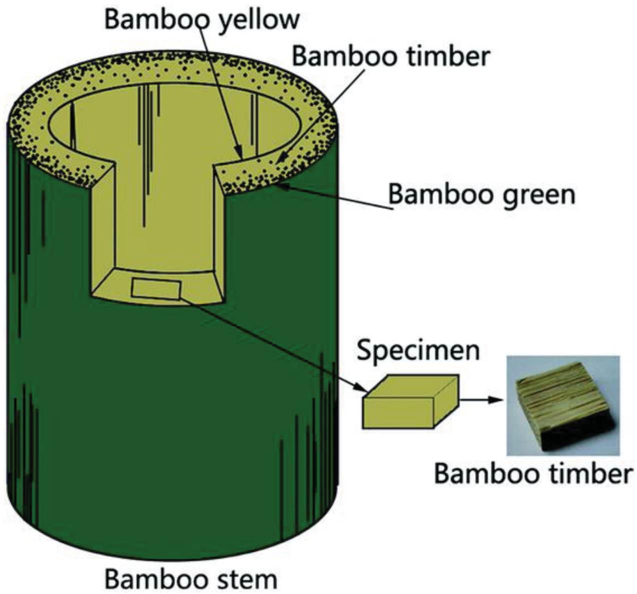


Plate 4-4: The anatomical structure of a bamboo stem (Li et al., 2015)

4.4.2 Sample blocks' trimming and viewing

An LKB 7800 knife-maker was used to make glass knives to cut the cured sample blocks into smaller blocks of approximately 60 mm^2 and 1 mm thick for trimming the samples into slices for analysis. The prepared blocks were then trimmed into approximately 0.03 mm thinner segmented pieces using an Ultramicrotome (Reichert-Jung Ultracut E). Sectioned segments of the samples were then transferred into a drop of water on a glass slide to hydrate. Using a heater stirrer plate, the slide was warmed to evaporate the distilled water. Then, 0.1 % Toluidine blue was used to stain the sample for 10 seconds, after which it was washed through with distilled water.

The slide was reheated to drive out the stain, and was viewed and captured using a Nikon DS-Ri1 high-resolution camera microscope at different magnifications, and an Olympus AX 70 fluorescence microscope through Nikon NIS software version 4.1.

4.5 HEAT PULSE VELOCITY WATER USE MEASUREMENTS OF BEEMA AND BALCOOA AT SHOOTER'S HILL, KWAZULU-NATAL

The HPV technique was only implemented at the KwaZulu-Natal site due to the larger culm diameters of the bamboo plants growing at Shooter's Hill, which enabled the insertion of the heater probes. The HPV system consisted of an 18-gauge hypodermic needle, with a 10 mm constantan heating wire at the distal end. The needle with the heater was 1.8 mm in diameter and 35 mm long. The needle heater was inserted into a brass tube with an outside diameter of 2.5 mm , which was inserted into the sapwood area. The thermocouples, made of type T copper-constantan, were embedded in polytetrafluoroethylene (PTFE) tubing with an outside diameter of 2 mm, and were equidistant (5 mm) from the central needle heater (Plate 4-6). They were inserted to the predetermined depths.

A single culm installation consisted of four pairs of probes (with each pair consisting of a needle heater and an upper and lower thermocouple), which were inserted radially to varying depths in the stem. The system was controlled, and data was collected using a CR1000 data logger (Campbell Scientific Inc., Logan, Utah, USA) connected to an AM 16/32B multiplexer (Campbell Scientific Inc., Logan, Utah, USA). This system was programmed to measure the hourly sap flow velocity.

The selected plants were monitored over an 18-month period (September 2018 to February 2020), allowing for an understanding of the seasonal variations in bamboo water use. To ensure that the data was not affected by outside variables, such as incoming solar radiation or heat loss, insulation foam was placed around the line heater and temperature probes. This also assisted in holding the probes in place.

4.5.1 Assessing the culm area of beema and balcooa culms

In order to understand the relationship between the culm diameter and the hollow diameter for installing HPV instrumentation, a survey was undertaken of cut culms that had been harvested. Vernier callipers were used to record the diameter and hollow diameter of each of the culms (Plate 4-5). These measurements (Table 4-1) were done to estimate the culm wall depth for the installation of the HPV probes. For the beema plants, no significant relationship ($R^2 = 0.22$) between culm diameter and hollow diameter was found (Figure 4-2). The data indicated an almost constant hollow diameter size of approximately 11.5 mm with a standard error of ± 0.5 mm. This data was used to estimate the HPV thermocouple probe insertion depths at 6.0 mm.

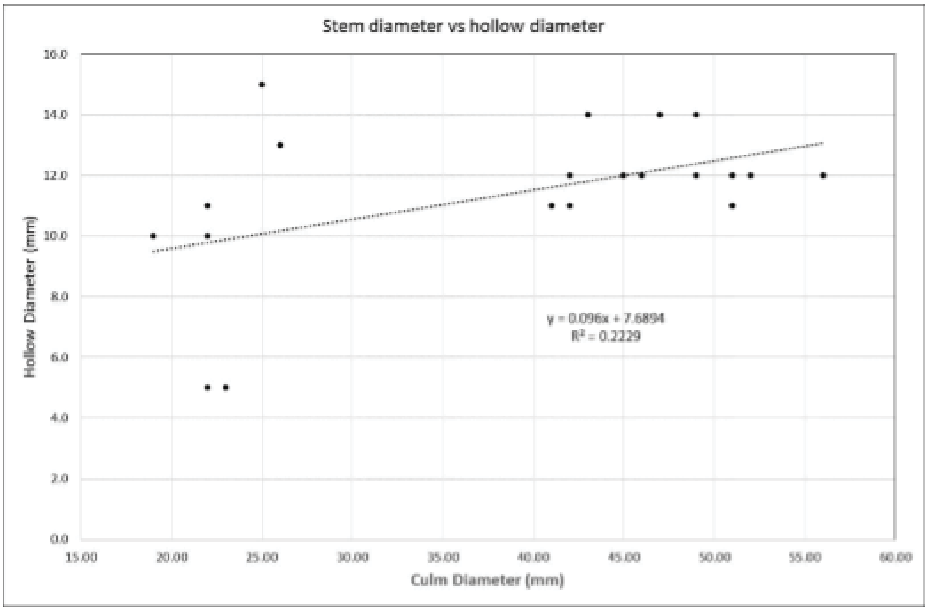


Figure 4-2: Regression of culm diameter vs hollow diameter for beema

Table 4-1: Stem diameters and areas of beema and balcooa bamboo at Shooter's Hill, KwaZulu-Natal

Bamboo species	Culm diameter (mm)	Culm area (mm^2)	Hollow diameter (mm)	Hollow area (mm^2)	Actual bamboo area (mm^2)
Beema	56	2463.01	12	113.1	2349.91
Beema	52	2123.72	12	113.1	2010.62
Beema	51	2042.82	12	113.1	1929.72
Beema	51	2042.82	11	95.03	1947.79
Beema	49	1885.74	14	153.94	1731.8
Beema	49	1885.74	12	113.1	1772.64
Beema	47	1734.94	14	153.94	1581.01
Beema	46	1661.9	12	113.1	1548.81
Beema	45	1590.43	12	113.1	1477.33
Beema	43	1452.2	14	153.94	1298.26
Beema	42	1385.44	12	113.1	1272.35
Beema	42	1385.44	11	95.03	1290.41
Beema	41	1320.25	11	95.03	1225.22
Beema	26	530.93	13	132.73	398.2
Beema	25	490.87	15	176.71	314.16
Beema	23	415.48	5	19.63	395.84
Beema	22	380.13	5	19.63	360.5
Beema	22	380.13	10	78.54	301.59
Beema	22	380.13	11	95.03	285.1
Beema	19	283.53	10	78.54	204.99

Balcooa	130	13273.23	105	8659.01	4614.21
Balcooa	130	13273.23	41	1320.25	11952.97
Balcooa	122	11689.87	78	4778.36	6911.5
Balcooa	121	11499.01	102	8171.28	3327.73
Balcooa	118	10935.88	92	6647.61	4288.27
Balcooa	115	10386.89	102	8171.28	2215.61
Balcooa	113	10028.75	94	6939.78	3088.97
Balcooa	111	9676.89	89	6221.14	3455.75
Balcooa	111	9676.89	86	5808.8	3868.09
Balcooa	110	9503.32	70	3848.45	5654.87
Balcooa	108	9160.88	58	2642.08	6518.8
Balcooa	107	8992.02	83	5410.61	3581.42
Balcooa	102	8171.28	82	5281.02	2890.27
Balcooa	102	8171.28	52	2123.72	6047.57
Balcooa	94	6939.78	74	4300.84	2638.94

Plate 4-5: Measuring different stem diameters and wall thickness of bamboo

4.5.2 HPV setup of beema and balcooa

Heat pulse velocity systems were installed at the two bamboo sites, following the principles of the heat ratio measurements, as detailed in Burgess et al. (2001). Eight culms were instrumented with HPV sensors for long-term monitoring in the beema and balcooa sites. Selected instrumented stems were 25 mm and 50 mm in diameter for beema (Plate 4-6) and 70 mm and 100 mm for balcooa (Plate 4-7).

Plate 4-6 Heater probes connected to a data logger and multiplexer

Plate 4-7: HPV installation in the balcooa clump at Shooter's Hill

Probes were initially installed at 2, 4, 6 and 8 mm for beema and at 4, 6, 8 and 10 mm for balcooa, and were located to represent four different concentric rings of the conducting area. This was necessary for up-scaling the water use of a single stem to the whole plant, as sap flow velocities can vary radially across the xylem. However, no prior information was available on which to base the approach (as bamboo represents a completely different anatomy to normal trees with heartwood), and the probe depths needed to be adjusted once a time series of sap velocity data had been analysed.

Sensors were connected to CR1000 data loggers and multiplexers, which were housed in a locked logger enclosure. Batteries to power the system were placed in safe boxes for security (Plate 4-8).

Plate 4-8: Safe boxes for batteries (grey boxes) and the logger enclosure (white box) in the beema site

4.5.3 Water use of *Eucalyptus grandis*

Four three-year-old *Eucalyptus grandis* trees were instrumented with HPV systems to monitor sap flow (Plate 4-9). Three CS616 probes were added to the eucalyptus site to determine soil water content. The data collected provided comparative estimates of the bamboo water use under similar climatic conditions.

Plate 4-9: Eucalyptus plantation at Shooter's Hill, KwaZulu-Natal

4.5.4 Water use of *Acacia mearnsii*

Four three-year-old black wattle trees were selected within the beema plantation site and were instrumented with HPV systems for monitoring sap flow (Plate 4-10).

The Campbell Scientific CS 616 TDR probes in the soil pit at the site were used to determine the total soil water profile. No additional CS616 probes were installed at the site because the previously installed CS616 probes were in the same vicinity at the beema site. It was assumed that the difference in water content between the beema and wattle plants was not significant. Therefore, the soil water content data collected from the beema plantation was presumed to be the same for the solitary wattle trees within the beema plantation (Plate 4-10).

Plate 4-10: Black wattle trees at Shooter's Hill, KwaZulu-Natal

4.6 STEM STEADY STATE

The Dynagauge collar is a precision thermodynamic electronic sensor that measures water flow rates and the accumulated daily totals of water lost through transpiration. The sensor is designed to convert transpiration to a mass flow rate when ancillary plant data (e.g. stem area) are combined in the logger software (i.e. the data is in g hr^{-1}) (Savage et al., 2000). The stem gauges have soft foam insulation that surround the electronics. The units were installed on a stem with an axial length of at least the gauge height.

One Dynamax Flow 32-1K sap flow system with a Flow 32B-1K expansion unit with the capacity to monitor 16 gauges (Dynamax, Houston, TX, USA) was installed at the beema site in KwaZulu-Natal (Table 4-3). At the balcooa site, a single Flow 32-1K sap flow base system was installed with two SGA100 gauges. At the Eastern Cape site, one Dynamax Flow 32-1K sap flow system with the capacity to monitor eight gauges was installed.

Each of these systems, which comprised a CR1000 data logger and an AM16/32B multiplexer (Plate 4-11) were powered by two 12V 100Ah RR2 deep-cycle batteries, installed in high-security safe boxes to prevent theft.

Plate 4-11: The wiring of the Dynamax system with a CR1000 data logger and an AM16/32B multiplexer with two adjustment potentiometers of the adjustable voltage regulator in the centre

A voltage control unit regulated the voltage output, depending on the number of collars and the size of the collars. The gauge's insulating sheath (referred to as a "collar") contains a system of thermocouples that measure temperature gradients associated with conductive heat losses vertically (up and down the stem) and radially through the sheath (Figure 2-11). This enabled the mass flow rate of the water in the stem to be calculated using Equation 4-1.

The specification of the gauge diameter is the determining factor for the selection of a gauge. Thus, at both the beema and balcooa sites, culms with matching diameters to the gauges were selected from the growth survey data.

At the beema site in KwaZulu-Natal, the selected gauges included one SGA70, six SGA50s, one SGA 40, four SGB25s, three SGEX25s and two SGB19s (a total of 16 gauges). At the balcooa site, two large SGA100 gauges were installed. The mechanical specifications of these gauges and the gauges selected with their constants are shown in Table 4-2 and Table 4-3, respectively.

At the Eastern Cape site, three SGEX25s were eventually used to obtain an estimate of the transpiration of the balcooa plants since all the culms at this site had a similar diameter.

Table 4-2: List of gauges used at the beema site and the initial programme constants and parameters used to measure sap flow

Box #	Sensor #	Sensor type	Ohms	Stem area (cm^2)	KST	dTmin	KSH1
Enclosure 1: Base	1	SGB 50	25.1	18.65	0.28	0.2	0.8
	2	SGB 50	26.9	18.65	0.28	0.2	0.8
	3	SGB 50	25.3	18.65	0.28	0.2	0.8
	4	SGB 70	20.6	63.6	0.28	0.2	0.8
	5	SGB 50	25.4	18.65	0.28	0.2	0.8
	6	SGB 50	26.4	18.65	0.28	0.2	0.8
	7	SGB 50	26.4	18.65	0.28	0.2	0.8
	8	SGA 40	39.7	11.44	0.28	0.2	0.8
Enclosure 2: 8 Gauge Expansion	9	SGB 25	41.7	4.13	0.28	0.2	0.8
	10	SGEX 25	41.2	4.13	0.28	0.2	0.8
	11	SGB 25	39.5	4.13	0.28	0.2	0.8
	12	SGB 25	41.7	4.13	0.28	0.2	0.8
	13	SGEX 25	41	4.13	0.28	0.2	0.8
	14	SGB 19	64.7	2.01	0.28	0.2	0.8
	15	SGB 19	62.7	2.01	0.28	0.2	0.8
	16	SGEX 25	41.1	2.01	0.28	0.2	0.8

Table 4-3: Mechanical specifications of the Dynamax gauges used at the beema site

Model No.	Shield height (mm)	Stem diameter (mm)			TC gap dX (mm)	Input voltage (V)	Input power (W)
		Min.	Typ.	Max.			
Stem flow gauge							
SGA9-ws	180	8	9	10	4.0	4.0	0.10
SGA10-ws	180	9.5	10	13	4.0	4.0	0.10
SGA13-ws	180	12	13	16	4.0	4.0	0.15
SGB16-ws	200	15	16	19	5.0	4.5	0.20
SGB19-ws	250	18	19	23	5.0	4.5	0.30
SGB25-ws	280	24	28	32	7.0	4.5	0.50
Trunk flow gauge							
SGB35-ws	460	32	41	45	10.0	6.0	0.9
SGB50-ws	505	45	50	65	10.0	6.0	1.4
SGB70-ws	610	65	70	90	13.0	6.0	1.6
SGB100-ws	660	100	110	125	15.0	8.5	4.0
SGB150-ws	1129	125	150	165	20.0	9.0	4.0

4.6.1 Preparation of bamboo culms for Dynagauge installation

Normal trunk preparation requires a reasonably smooth stem since good thermal contact is key to obtaining the temperature of the xylem, and the heat flow into the xylem. In general, the least amount of disturbance is best. For bamboo, this was easily facilitated by the already smooth shiny outer surface of the culm, which obviated the need for the careful sanding of any loose or rough bark. Another advantage of bamboo is that the culm diameter is essentially constant in the first few meters from the base, making the selection of the median diameter relatively easy.

Once the culm's position was selected for a suitable gauge, it was cleaned to remove any dust and grit, and then sprayed around the circumference with canola release spray in the region of the expected heater position to prevent the sensor from sticking to the stem (Plate 4-12).

Plate 4-12: Preparation and installation of the Dynamax collars

During installation, the following precautions were taken:

- The gauge was orientated in the correct direction to measure flow.
- The gauge was the correct size to prevent damage to the components.
- The heater strip was carefully tucked inside the insulation foam.
- The velcro straps were tightened to ensure a snug fit.
- The stem gauge heater resistance was recorded for use in the program.
- The sensor cable was attached and sealed with insulation tape.

Finally, the aluminium bubble wrap was wrapped around the sensor, and it was secured with cable ties (Plate 4-12). The upper opening was then sealed with plastic wrap to prevent moisture ingress from above (Plate 4.13). Once all the gauges had been installed and the electrical cables connected, the battery power could be applied and the adjustable voltage regulators (AVRDs) could be adjusted using a voltage meter to match the recommended voltages for the relevant gauge. The program was then launched with the entered user constants for each gauge, as shown in Table 4-3.

A B

Plate 4-13: A) Securing the sensor; and B) Completed Dynamax collar installation

4.6.2 Automatic zero set

In the CRBasic program, the flag for automatic zero set was set using the Ksh values between 04:00 and 06:00. Ksh is the sheath conductance and is calculated when the plant has established a non-flow condition. The data was monitored and the apparent Ksh measured.

The data was then retrieved from the logger and updated with the user constants. K_{sh} proportionally relates the C_h signal (the radial heat thermopile voltage) directly to the radial heat Q_r. The calculation for K_{sh} was determined by solving the energy balance equation when setting $Q_f = 0$ as follows:

$$P_{in} = Q_r + Q_v$$

Equation 4-2: Power input to a stem from the heater

Where P_{in} is the power input to a stem from the heater, Q_r is the radial heat conducted through the gauge to the ambient, and Qv is the vertical heat conduction.

$$Q_r = P_{in} - Q_v$$

Equation 4-3: Radial heat flux equation

$$Q_r = K_{sh} \text{x} \, (\text{C} - H_c)$$

Equation 4-4: Radial heat loss equation

Where Ksh is the thermal conductivity of the stem and $C\text{-}H_c$ is the temperature difference measured in channel CH.

After computing P_{in} and Q_v to the usual sap flow computation, the thermopile signal $C\text{-}H_c$ (mV) was divided into the remaining heat flux. The minimum apparent K_{sh} value was obtained at a minimum flow rate, the zero-set point. Each of the Dynamax sensors was then calibrated and the K_{sh} was updated.

4.6.3 Data output

The data output from the Dynamax systems is in g hr^{-1} (using the specific heat of water). The conversion to ℓ day^{-1} is as follows:

- Convert g hr^{-1} (x) to latent heat flux:

$$L_v F (W \; m^{-2}) \colon (\frac{1000x}{3600})$$

- Convert ƛ ET (W m^{-2}) to ET (mm day^{-1}) where ƛ = 2454000 J kg^{-1} :

$$\frac{x}{245400} \text{ x } 3600$$

- 1 kg m^{-2} of water is equal to 1 mm.
- Therefore, sap flow is in mm.hr^{-1} × area of the stem provides ℓ hr^{-1}
- Summed for the day provides ℓ day^{-1}

4.7 CROP COEFFICIENT (K_C)

Crop coefficient refers to the ratio of measured crop evapotranspiration and the reference grass evapotranspiration under similar condition, normally denoted as ET_0 (Allen et al., 1998). The crop coefficient (K_c) is affected by the crop characteristics, management practices and environmental aspects (Savva & Frenken, 2002). Other factors may include ground cover and planting density. Mature crops are characterised by $K_c > 1$ (Allen et al., 1998).

The purpose of calculating the crop coefficient lies in its effectiveness in irrigation planning and design, as well as management (Savva & Frenken, 2002). In this study, K_c was calculated from the actual evaporation measured at each site and the reference evaporation (ET) from the nearby AWS. Crop coefficient was calculated as:

$$K_c = \frac{ET_{crop}}{ET_0}$$

Equation 4-5: Crop coefficient equation

Where ET_{crop} is the evapotranspiration of the crop (mm day^{-1}), K_c is the crop coefficient (dimensionless), and ET_0 is the reference grass evapotranspiration (mm day^{-1}).

CHAPTER 5: RESULTS

5.1 KWAZULU-NATAL

5.1.1 Meteorological data

An automatic weather station was installed at Shooter's Hill to provide hourly and daily meteorological data for input when performing calculations to determine the ET_0 (Allen et al., 1998). It also provided data for interpreting the impact of the environment on the hourly sap flux density and water demand of the different land uses measured at the study site. Diurnal and daily trends were measured for solar radiation, air temperature, relative humidity, wind velocity and rainfall. The data was collected from September 2018 (spring) to February 2020 (summer).

From September 2018 to March 2019, daily total incoming solar radiation increased markedly from 15 to ~ 32 MJ, especially in January and February 2019 (summer) when most days exceeded 27 MJ (Figure 5-1). In mid-summer (January 2019), a maximum reading of incoming solar radiation of 32 MJ was recorded at Shooter's Hill (Figure 5-1). By contrast, in winter (May to August 2019), when solar angles were lower, the average minimum incoming solar radiation recorded was only 13 MJ, with a few clear warm days reaching 15 MJ (Figure 5-1). The lowest incoming solar radiation recorded was ~ 2.4 MJ on 14 August 2019, which was a cold, cloudy winter's day.

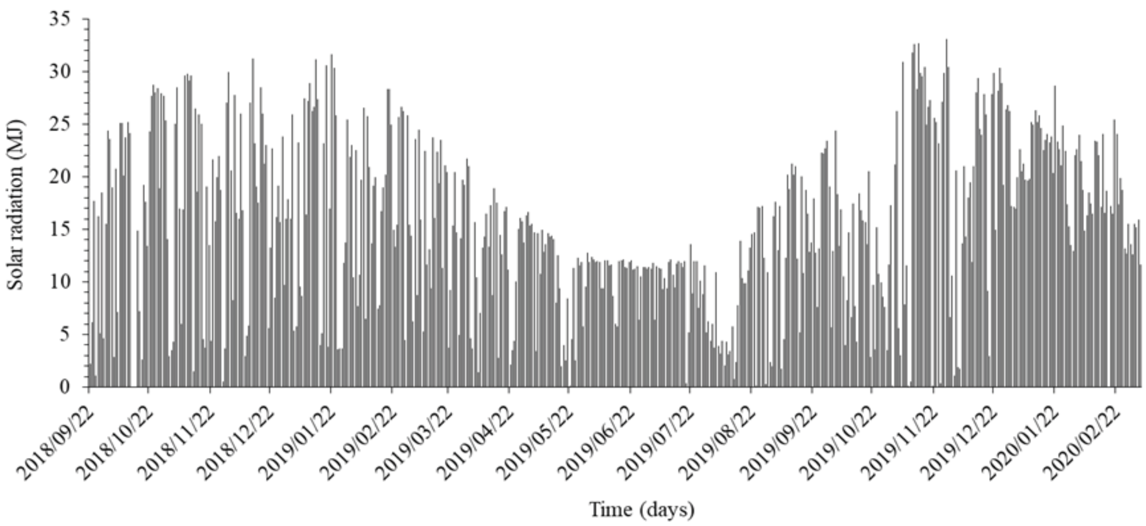


Figure 5-1: Daily total incoming solar radiation from September 2018 to February 2020 at Shooter's Hill, KwaZulu-Natal

Average daily air temperatures exceeding 23 °C were regularly recorded from September 2018 to March 2019 and from September 2019 to February 2020 (spring to summer) (Figure 5-2), which is indicative of the warm summer conditions in the Pietermaritzburg district, coinciding with the high daily total incoming radiation conditions (~ 32 MJ) described above. Minimum average temperatures of < 20 °C were also noted from May to August 2019 (winter), with temperatures ~ 16 °C in July and August 2019 (Figure 5-2).

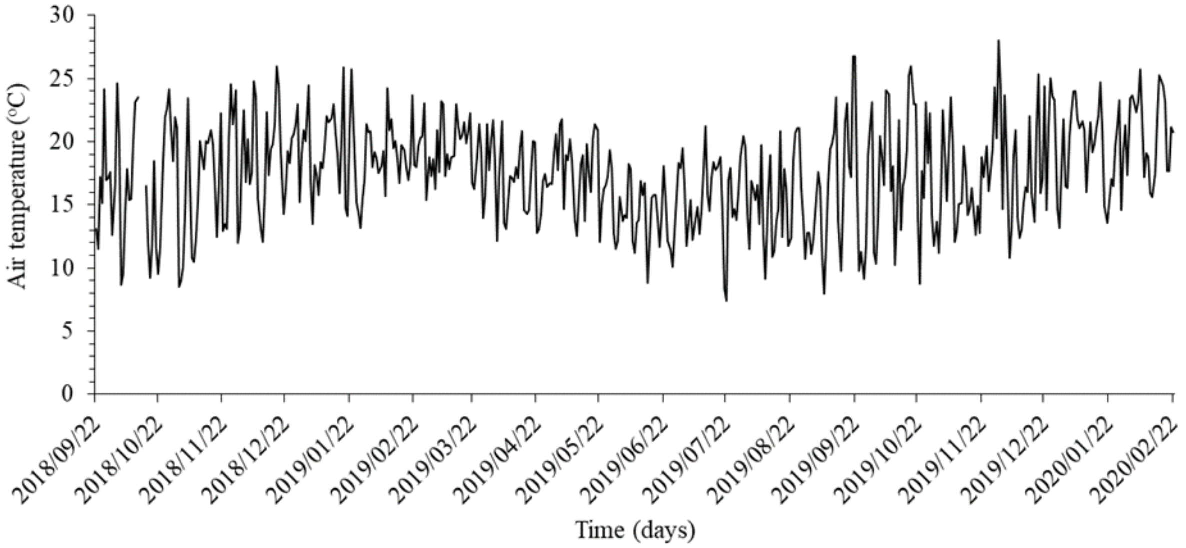


Figure 5-2: Daily average ambient air temperature from September 2018 to February 2020 at Shooter's Hill, KwaZulu-Natal

With an increase or decrease in solar radiation, air temperature also increased or decreased at Shooter's Hill. For example, in August 2019, solar radiation was recorded to be ~ 16 MJ, increasing to ~ 30 MJ in November 2019, while average air temperatures recorded in August and November 2019 were ~ 20 °C and 28 °C, respectively (Figure 5-2). With the decrease in solar radiation from 25 to 14 MJ between March and June 2019, air temperature also showed a concomitant decrease from ~ 21 to 15 °C.

Daytime (06:00–18:00) rather than average daily relative humidity (RH) data is presented here due to the bias caused by the saturated conditions at night (dew), when the RH was generally 100%. Daytime relative humidity > 70% was observed from September 2018 to March 2019, and from September 2019 to February 2020 (the spring to summer period) (Figure 5-3). A maximum RH of 100% was frequently reached between September 2018 and February 2020 on moist rainy days. During the dry winter period, from May to August 2019, the RH recorded was generally < 40% (Figure 5-3). The minimum RH was assumed to be caused by dry air. However, Shooter's Hill was considered humid in summer and dry in winter over the study period.

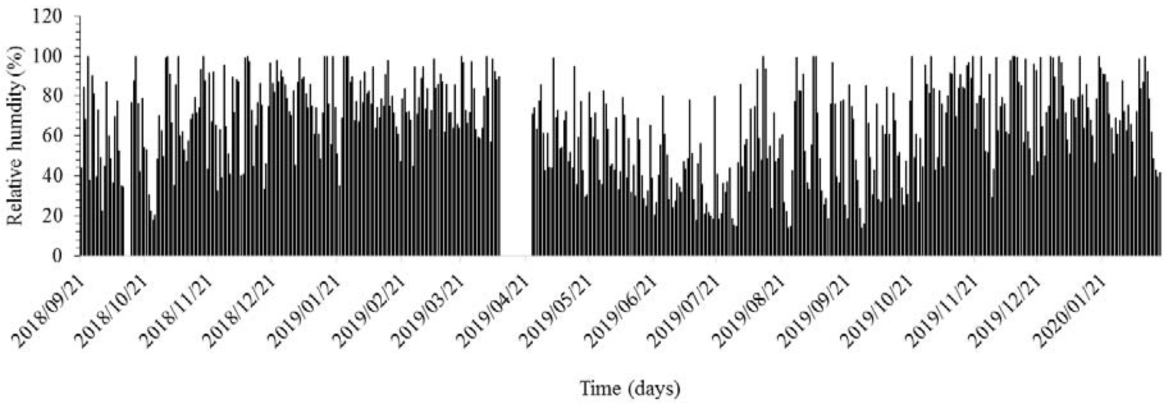


Figure 5-3: Daily relative humidity measured at the Shooter's Hill grassland site from September 2018 to February 2020

From September 2018 to April 2019, frequent daily rainfall events exceeding 15 mm were recorded at Shooter's Hill, with the highest rainfall of 80 mm being recorded in February 2019, followed by 55 mm in April 2019 (Figure 5-4). The highest monthly recorded summer rainfall was 255 mm in November 2019, followed by 230.6 mm in February 2019 and 229.3 mm in January 2020 (Table 5-1).

With the onset of winter, the rainfall ceased, with only a few rainfall events (< 4 mm) recorded between May and September 2019. From September 2019, regular rainfall events of > 10 mm were recorded (Figure 5-4). During the 2018/19 hydrological year (September 2018 to October 2019), 1304.9 mm was recorded at the site. A further 799.6 mm was recorded for from November 2019 to mid-February 2020. With a total of 2 104.5 mm for the 17-month study period, the site was therefore considered “wet”.

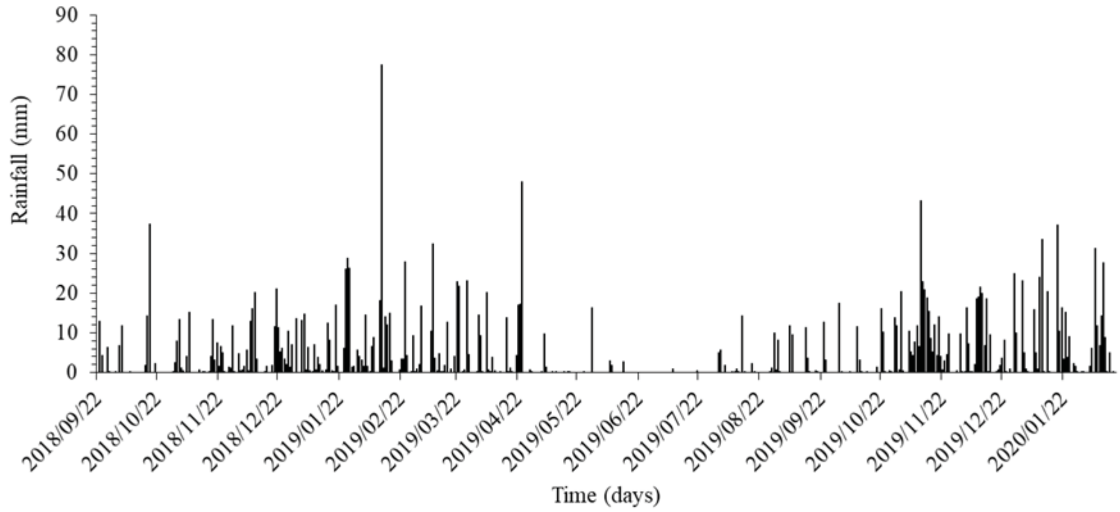


Figure 5-4: Daily rainfall measured at the Shooter’s Hill grassland site from September 2018 to January 2020

Table 5-1: Total monthly measurements of solar radiation, relative humidity, air temperature and rainfall at Shooter’s Hill

Timestamp	Solar radiation (MJ m^{-2})	Relative humidity (%)			Air temperature (°C)			Rainfall (mm)
	Sum	Average	Max	Min	Average	Max	Min	Sum
Oct-18	567.3	75.9	100.0	26.5	19.1	32.1	5.8	77.5
Nov-18	494.3	88.4	100.0	46.3	18.8	32.4	7.5	99.6
Dec-18	561.0	91.7	100.0	41.7	21.2	34.3	11.3	163.7
Jan-19	561.3	92.7	100.0	24.5	20.8	35.5	11.5	186.3
Feb-19	506.1	95.0	100.0	51.5	21.3	32.9	12.3	230.6
Mar-19	497.8	93.5	100.0	56.2	21.3	30.6	11.2	164.7
Apr-19	355.6	91.4	100.0	46.6	18.4	27.4	10.9	152.7
May-19	318.9	74.2	99.9	31.7	18.7	28.4	8.1	28.7
Jun-19	326.4	62.0	100.0	12.6	16.4	25.7	5.1	7.4
Jul-19	308.3	42.9	99.9	10.8	17.6	27.9	1.8	1.3
Aug-19	241.3	73.2	100.0	19.3	16.9	29.0	6.8	51.3
Sep-19	457.5	70.4	100.0	15.9	19.0	35.2	4.5	53.4
Oct-19	366.9	84.0	100.0	30.3	20.3	35.0	6.2	87.7
Nov-19	602.6	89.3	99.9	35.0	19.8	35.3	9.0	255
Dec-19	603.0	88.8	100.0	36.0	19.6	36.4	8.7	201.4
Jan-20	669.4	94.8	100.0	56.9	21.9	32.2	11.5	229.3
Feb-20	532.0	87.9	99.9	42.2	23.2	31.9	14.2	172.9
Mar-20	495.7	90.0	99.9	57.0	19.0	23.2	12.7	113.3
Apr-20	462.8	87.2	100.0	47.6	16.5	22.3	12.0	116.4
May-20	170.7	70.5	99.9	25.1	15.2	18.2	7.5	12.4
Total	**9098.9**							**2405.6**

Wind velocity monitored at Shooter's Hill showed no noticeable or seasonal daily patterns, with daily average wind speeds generally < 3 m s^{-1} (Figure 5-5). However, some days experienced high wind speeds. For example, in November 2018, a high average wind speed of ~ 7 m s^{-1} (25 km hr^{-1}) was recorded (Figure 5-5). On 11 November 2018, the maximum hourly wind was 9.145 m s^{-1} (32.7 km hr^{-1}). Therefore, the effect of wind speed as a driver of transpiration was considered to be small in the assessment of the evaporation rate of the various land uses studied.

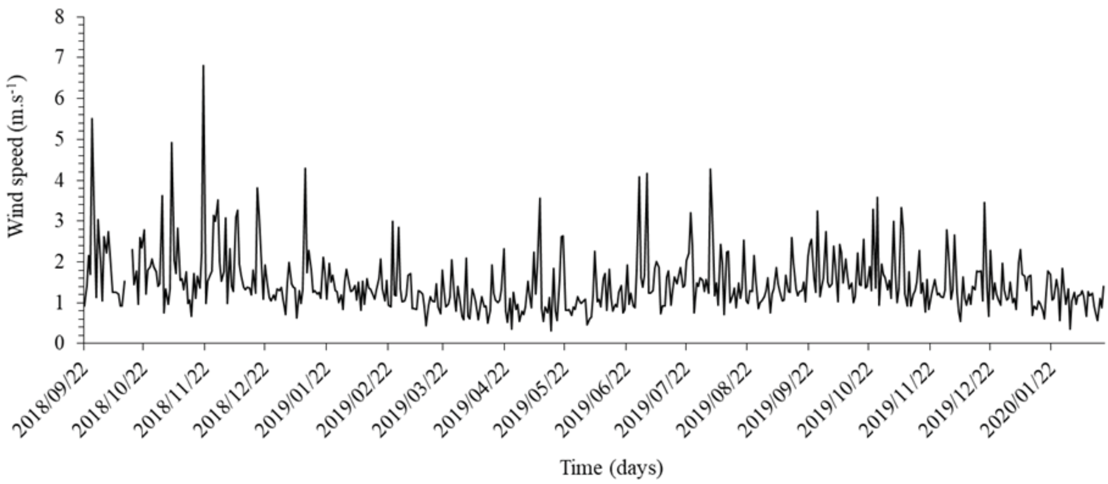


Figure 5-5: Average daily windspeed measured at the Shooter's Hill grassland site from September 2018 to February 2020

An important measurement in modelling the impact of different land uses is the determination of ET_0 (Figure 5-6). This parameter was calculated from the 30-minute weather variables for Shooter's Hill and used to determine the crop factors for the different land uses studied. Clear summer days averaged ~ 6 mm day^{-1}, compared to ~ 2 mm day^{-1} in winter (Figure 5-6).

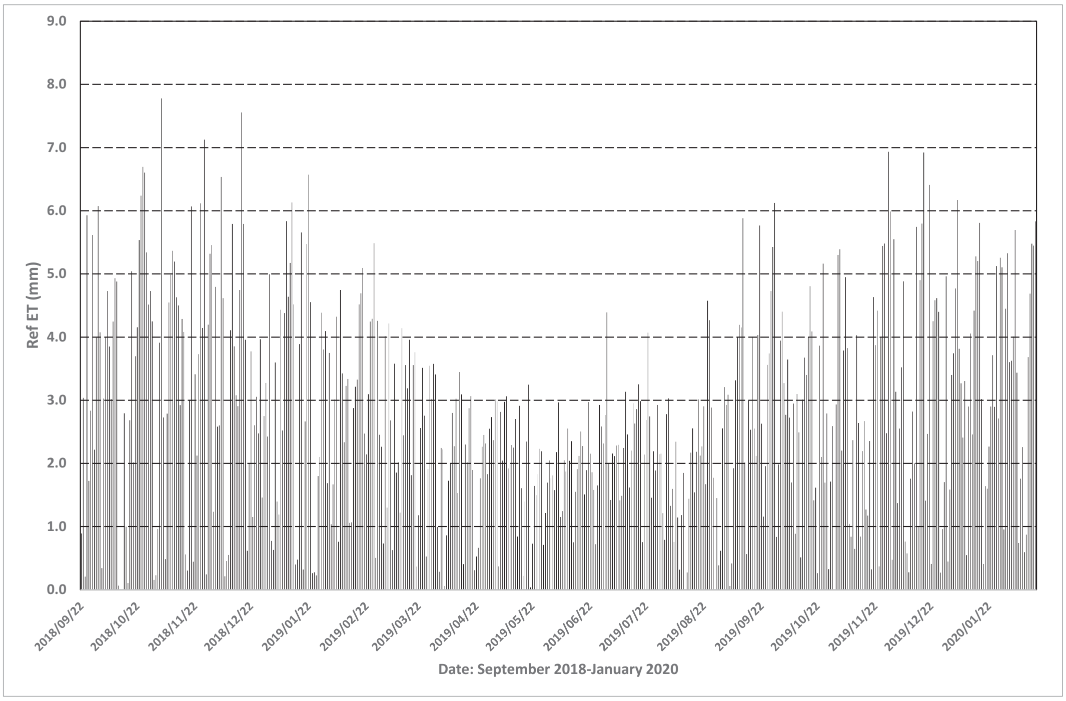


Figure 5-6: FAO 56 reference evaporation for Shooter's Hill

5.1.2 Soil profile water content

At the beema site, the equivalent soil water content (SWC) measured at different soil depth levels was recorded with the topsoil (0–200 mm) > 40 mm from October 2018 to February 2020. Other SWC values recorded were frequently > 60 mm (January to May 2019), corresponding with high rainfall events exceeding 15 mm. From January to May 2019, the water contents in the intermediate soil depth (> 300 to < 500 mm) was > 30 mm, while deeper soil depths (500–800 mm) were generally > 35 mm and remained wetter than the topsoil during the dry period (Figure 5-6). In the topsoil, low rainfall of < 4 mm recorded from June to August 2019 resulted in a reduction in the SWC from > 80 mm in May 2019 to < 35 mm in July 2019. However, from November 2019 to February 2020, peaks exceeding 60 mm were noted with the continuous increase in daily rainfall events from ~ 15 to 40 mm (Figure 5-7). It was also noted that, from May to November 2019, low rainfall only increased the soil water in the topsoil from 19 to 34 mm, while the SWC in the intermediate and deeper depths (> 300–800 mm) remained constant until rain infiltrated, as the rainfall accumulated by the end of October 2019. It is important to note that the plant available water (water between field capacity and permanent wilting point) was not determined through soil characteristic studies, which were beyond the resources of this study.

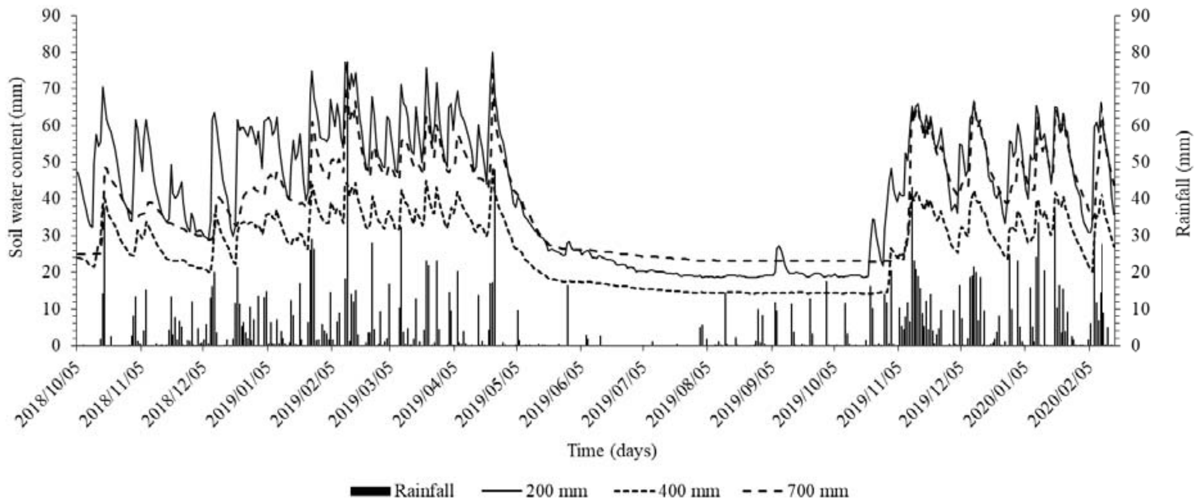


Figure 5-7: Rainfall and soil water content with respect to soil depth at the beema site, KwaZulu-Natal

Total soil profile water content (TSPWC) for the 800 mm deep soil profile varied from 60 to 190 mm from October 2018 to February 2020 (Figure 5-8). Irregular rainfall events > 15 mm caused large fluctuations of ~ 80 to 190 mm in TSPWC from October 2018 to May 2019. A TSPWC of ~ 190 mm was recorded from February to April 2019, with a total of 548 mm recorded during this period (Figure 5-8). In contrast, the reduction in the TSPWC from 160 mm in May 2019 to < 90 mm from June to October 2019 was associated with the decrease in rainfall from ~ 201.1 mm in May 2019 (Figure 5-8) to a low of 8.7 mm recorded in June and July 2019 (Table 5-1). The TSPWC at the beema site remained constant at ~ 60 mm from September to October 2019 (Figure 5-8) when there were few rainfall events. Assuming that the wetter conditions corresponded with the field capacity (FC), and the driest conditions corresponded with the permanent wilting point (PWP), the maximum plant available water (PAW) was ~ 120 mm in the summer.

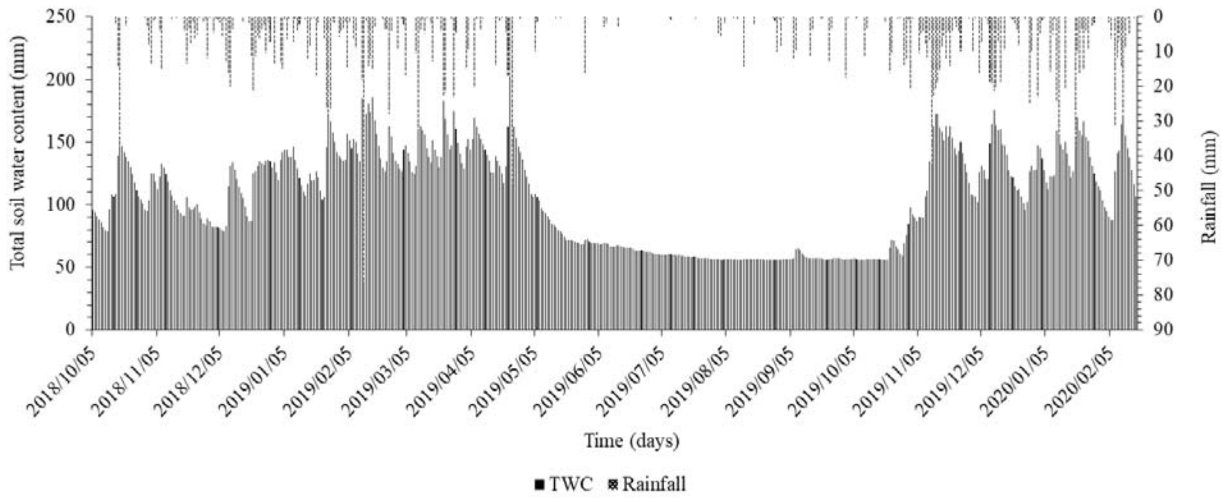


Figure 5-8: Total soil water content and rainfall at the beema site, KwaZulu-Natal

The SWC data was collected at the balcooa site from September 2018 to February 2020. Rainfall events > 15 mm day^{-1} occurred frequently between September 2018 and April 2019, resulting in an increase in soil water content from 59 mm in September 2018 to > 78 mm in November 2019 (Figure 5-9). By contrast, rainfall < 4 mm fell at the study site between May-August 2019 and resulted in a decrease of SWC from 80 mm in April 2019 to < 40 mm in June-July 2019 (Figure 5-9).

The SWC was higher (> 50 mm) in the deepest soil depth (500–800 mm) than in the shallower (0–200 mm) and intermediate soil depth (> 200 to < 500 mm), which was < 50 mm and < 41 mm from May to August 2019 (Figure 5-9) when rainfall was low (< 4 mm). Therefore, the increase in rainfall by a total of ~ 940.7 mm from September 2019 to February 2020 caused the deepest depth (700 mm) to accumulate > 80 mm of TSPWC by December 2019 (Figure 5-9).

Over the study period, the TSPWC ranged between 80 and 190 mm in the 800 mm soil profile at the balcooa site. For example, the TSPWC increased from ~ 122 mm in September 2018 to 170 mm in October 2018 when rainfall exceeded 20 mm from October 2019 to February 2020 (Figure 5-9). With the cessation of rain in winter (June to July 2019), when only 8.7 mm of rain fell, there was a rapid decrease in the TSPWC from 150 mm in May 2019 to < 100 mm in July 2019 (Figure 5-10). Assuming the wetter conditions corresponded with the FC and driest conditions corresponded with the PWP, the maximum PAW was ~ 150 mm in the summer.

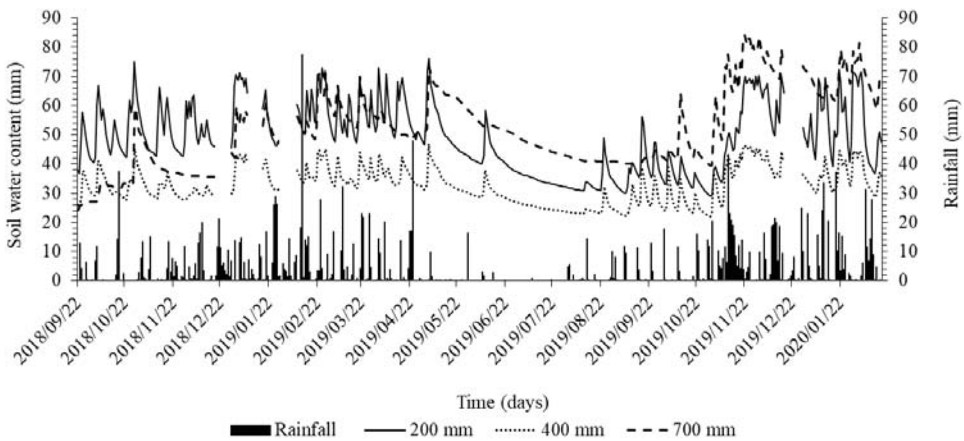


Figure 5-9: Rainfall and soil water content with respect to soil depth at the balcooa site, KwaZulu-Natal

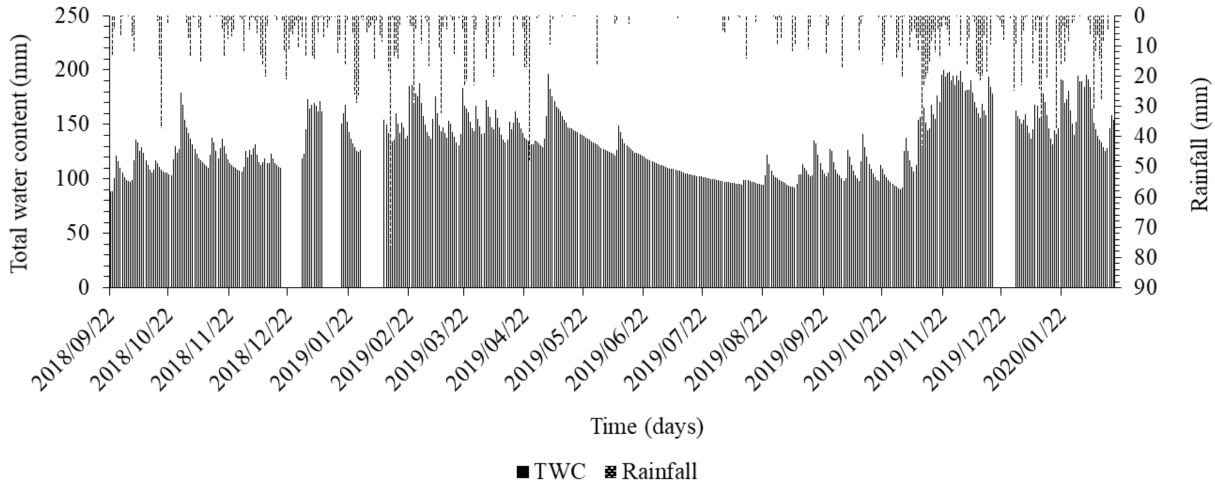


Figure 5-10: Total soil water content and rainfall at the balcooa site, KwaZulu-Natal

The SWC data for the eucalyptus site was collected from May 2019 to February 2020. There was a constantly decreasing SWC in the topsoil between May and October 2019, from 69 mm to 45 mm, coinciding with the low rainfall events (< 20 mm). Increasing daily rainfall from ~ 20 mm to 45 mm from November 2019 to February 2020 caused an increase in SWC to > 60 mm, with topsoil reaching 80 mm when high summer (November) daily rainfall events of ~ 45 mm were recorded (Figure 5-11).

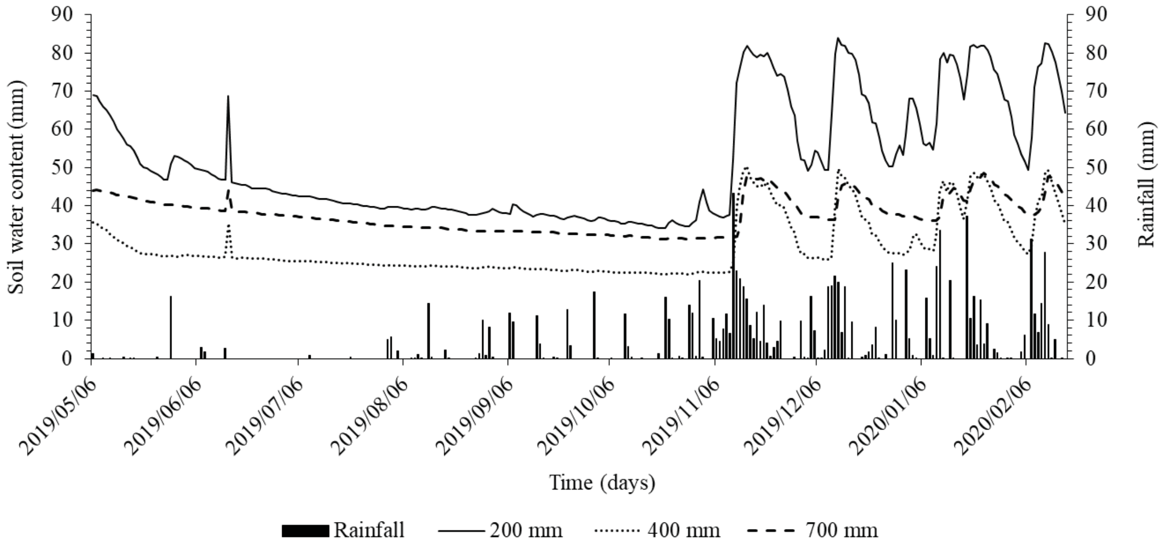


Figure 5-11: Rainfall and soil water content with respect to soil depth at the eucalyptus site, KwaZulu-Natal

A total rainfall of only 87 mm between June and July 2019 resulted in a steady decline in TSPWC from 140 mm to 100 mm from May to November 2019 (Figure 5-12). However, high summer daily rainfall of > 15 mm recorded frequently between November 2019 and February 2020 caused the TSPWC to exceed 170 mm (Figure 5-12). Assuming the wetter conditions corresponded with the FC and the driest conditions corresponded with the PWP, the maximum PAW was ~ 100 mm in the summer.

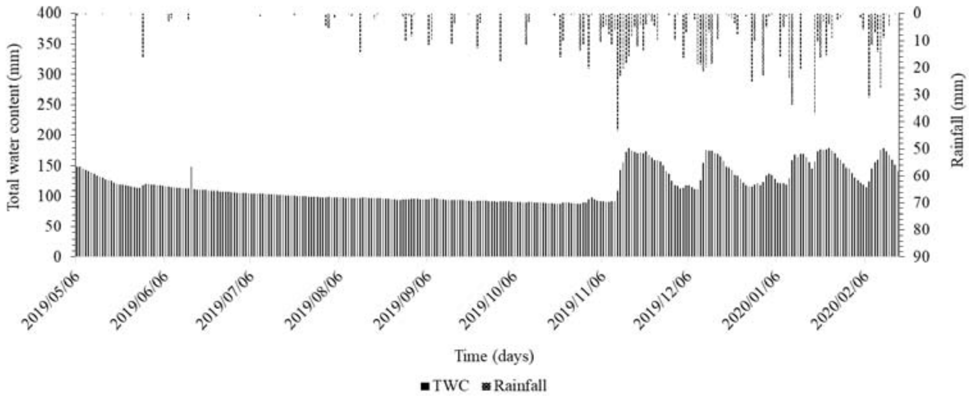


Figure 5-12: Total soil water content and rainfall at the eucalyptus site, Shooter's Hill, KwaZulu-Natal

5.1.3 Growth of *Bambusa balcooa*

There was a notable difference between the culm diameters measured at breast height between the balcooa and beema plantations. With the DBH ranging from 10 to 69 mm in the beema plantation, and between 30 and 109 mm in the balcooa plantation, the data showed that the balcooa culms had larger culm diameters than the beema culms (Figure 5-13). Therefore, these culms were classified according to different size classes to understand the distribution of diameter sizes. The data had a normal distribution, with 54% of the 251 beema culms measured falling into the 30–49 mm size class. By contrast, 54% of the 63 balcooa culms measured fell into the 80–99 mm size class (Figure 5-13). The balcooa culms were characterised by a lower number of culms, but with significantly higher culm diameters. Optimal growth was expected due to the high rainfall events (2 104.5 mm) recorded at Shooter's Hill during the study period.

The bema bamboo culms at Shooter's Hill had an 8.0% increase in diameter from a mean of 34.0 ± 5.6 mm to 37.4 ± 9.5 mm over the 18-month study period (Table 5-2). There was an increase of 38 beema culms over the study period from 213 culms measured in September 2018 (Table 5-2). The high standard deviation in the beema plantation indicated the high variability of culms. Balcooa culms only had a 4.0% increase in diameter from a mean of 77.30 ± 14.49 mm to 79.33 ± 14.91 mm over the same period (Table 5-3). The standard deviation in the balcooa plantation was also high, showing high a variability of culms. When assessing the growth of bamboo and its potential for biomass production for rural areas, other growth parameters may be considered.

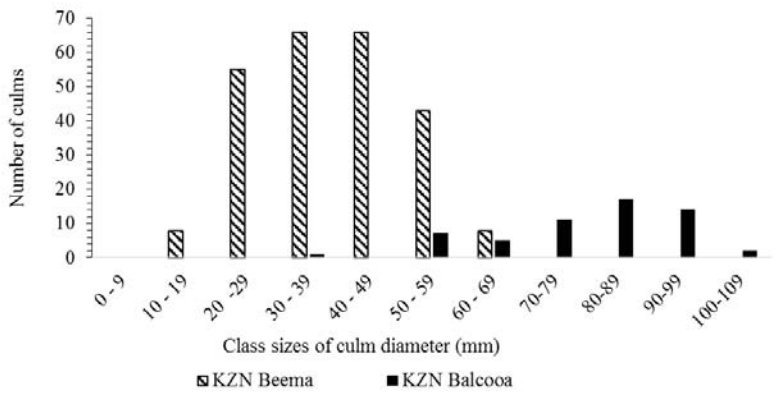


Figure 5-13: Frequency size classes of beema and balcooa bamboo

Table 5-2: Culm diameter measurements of bema bamboo

Clump	Total culms/clump 13/08/2018	03/02/2020	Average culm diameter (mm) 13/08/2019	03/02/2020
1	17	20	34.4	36.4
2	9	9	33.4	34.7
3	14	14	33.3	33.5
4	6	6	27.7	23.8
5	19	21	36.1	40.8
6	24	24	42.5	47.9
7	6	9	40.6	42.3
8	5	6	26.7	30.0
9	20	22	38.6	41.2
10	5	7	32.5	35.3
11	1	2	19.0	19.5
12	14	16	35.1	37.2
13	11	12	28.6	31.1
14	7	8	30.9	33.4
15	14	18	40.2	43.1
16	9	11	37.2	40.3
17	8	11	32.9	38.3
18	2	4	32.0	39.8
19	17	24	41.1	66.8
20	2	3	34.8	29.2
21	3	4	37.3	40.5
Total number of culms			**213**	**251**
Mean			**34.0**	**37.4**
sd			**5.56**	**9.46**

Table 5-3: Summary of culm diameter measurements of balcooa bamboo

Clump	Total culms/clump 13/8/2018	25/02/2020
1		
Total number of culms	56	63
Mean	77.3	79.33
sd	14.49	14.91

The Li-Cor plant canopy analyser was used to estimate LAI for the bamboo plantation, and the eucalyptus and black wattle trees, together with their corresponding radial growth. Data was collected from April to December 2019. However, for calibration purposes, only data from April to September 2019 was considered to be valid. The LAI of a plant canopy is defined as its leaf area per unit of ground area (Breda, 2003). This is an important parameter in water use studies as it measures the photosynthetic active area and the area of transpiration.

Increase in the LAI from 4.8 in the dry winter (April) to 7.2 in the early summer (September) showed the contribution and effects of moisture and solar energy on beema bamboo growth (Figure 5-14). By contrast, approximately 5.2 was recorded in the balcooa site in April 2019. This was slightly higher than the initial LAI in the beema plantation. The balcooa culms were characterised by an extensive leaf and culm structure. Therefore, high LAIs were recorded at the beginning of August (> 6.4) in the balcooa site, with a maximum value of 7.0 recorded in September when rainfall and temperatures were higher.

Low LAIs (~ 4.0) were recorded in the eucalyptus plantation in April 2019, compared with the other land uses at Shooter's Hill in the same month (Figure 5-14). Fluctuating LAIs were recorded in winter, ranging from 3.8 to 4.8 (April to July), followed by increasing rates of 5.0 and 7.0 from August to September, respectively.

Winter LAIs of ~ 5.0 were recorded in April to June in the black wattle trees. These were 18% higher than the value in the eucalyptus. Similar values were recorded between beema and black wattle since the trees were located within the beema plantation. High summer values reaching 7.0 were recorded in August and September (Figure 5-14).

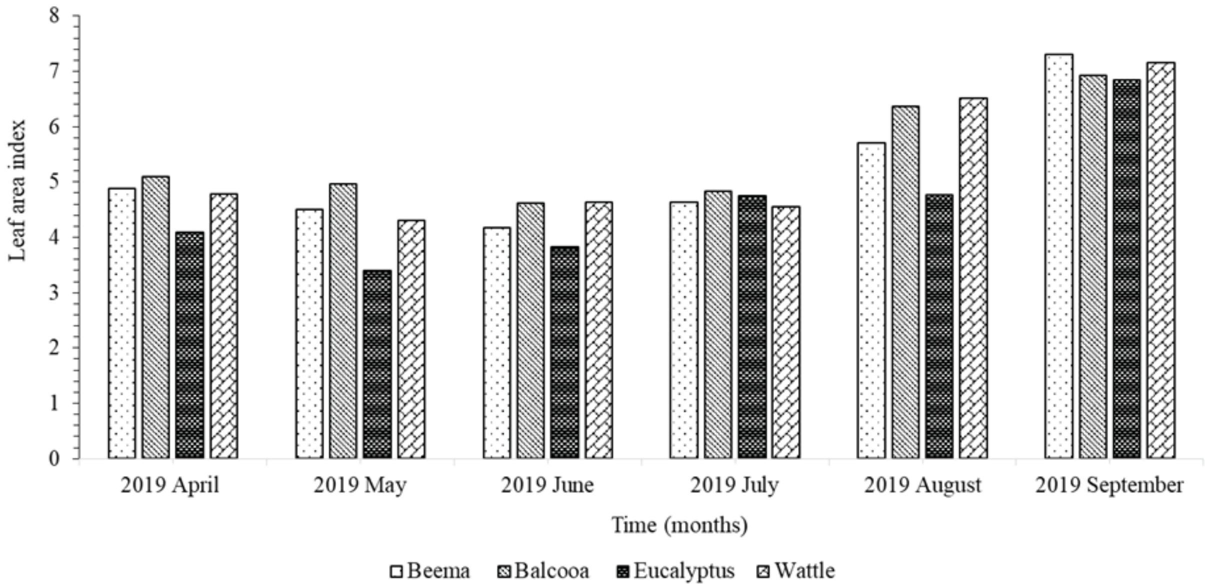


Figure 5-14: Leaf Area Index of beema, balcooa, eucalyptus and black wattle at Shooter's Hill

Increases in average stem diameters from ~ 102 mm in April 2019 to 151 mm in January 2020 were observed in the eucalyptus trees (Figure 5-15). Eucalyptus stems were increasing at an average of ~ 2 mm month^{-1}, resulting in a maximum average diameter of 151 mm in January 2020 (Figure 5-15).

Canopy measurements of the black wattle trees were not possible since the results were compromised by the dominant beema canopy. An increase in average black wattle stem diameters from an initial 116 mm in April 2019 to 164 mm in January 2020 showed ~ 48 mm growth within the 10- month period (Figure 5-15). The rates of tree growth for black wattle and eucalyptus were ~ 2–3 mm month^{-1}.

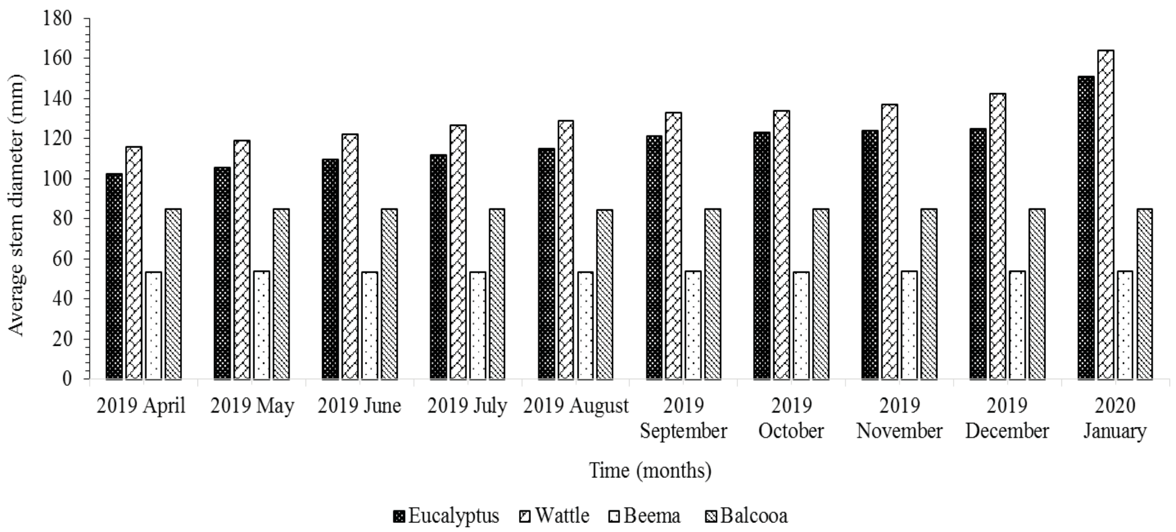


Figure 5-15: Average stem diameters of beema, balcooa, eucalyptus and black wattle trees at Shooter's Hill

5.1.4 Bamboo anatomy

Bamboo culms were viewed with a scanning electron microscope (SEM) and under 10 and 40 x magnification with a light microscope to identify key cellular contents such as xylem tissues and the vascular tissue arrangement. The SEM images showed four rings of vascular bundles, fibre sheaths and parenchyma cells (Plate 5-1). The xylem cells were associated with phloem cells to form the vascular bundle (Plate 5-2). At least three vascular bundles were observed in the 1 x 1 mm^2 culm section (Plate 5-1).

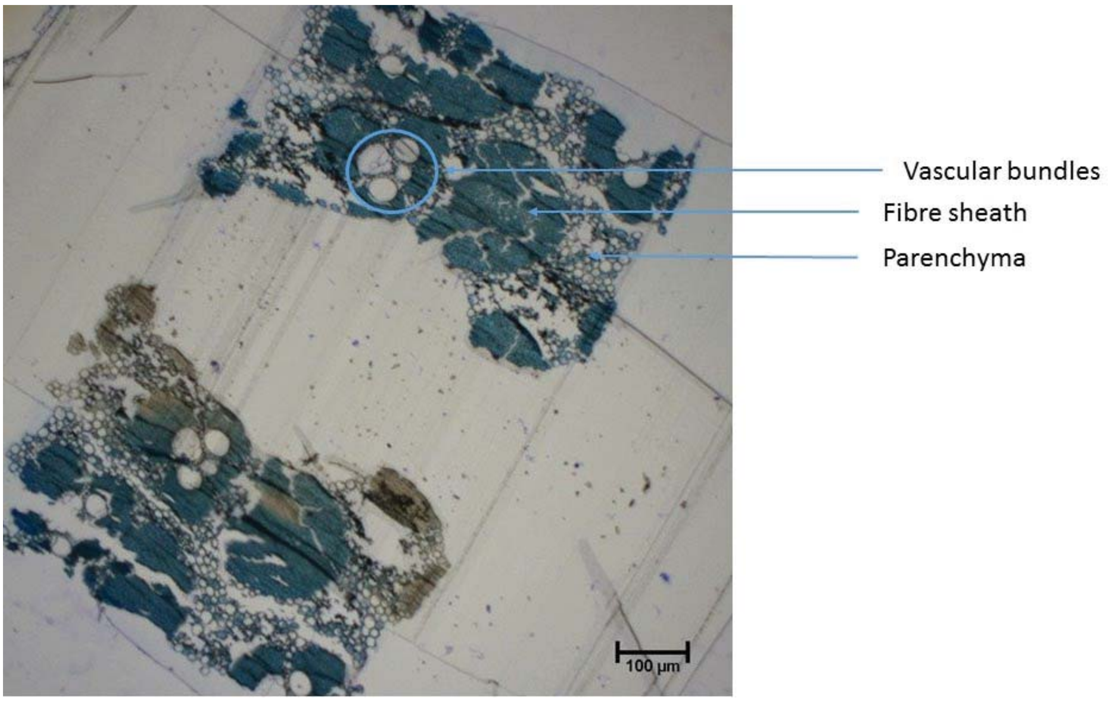


Plate 5-1: Cross-sectional layout of beema cellular structures

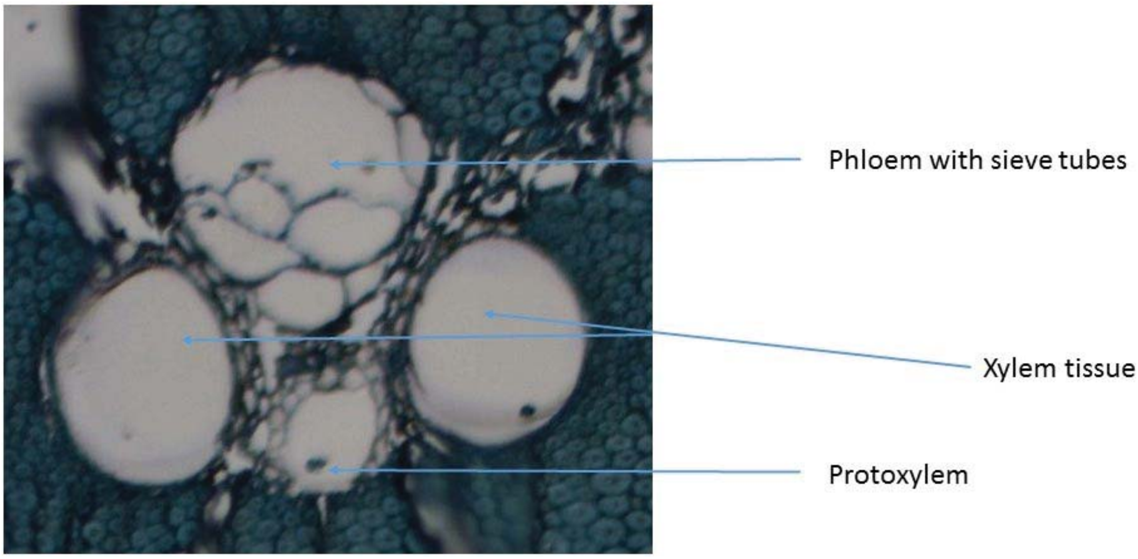


Plate 5-2: Anatomical structure of a beema vascular bundle

The 6 x 4 mm^2 beema cross-sectional area was viewed under a light microscope and at least 41 vascular bundles were identified (Plate 5-3). Therefore, the 44.9 mm beema culm harvested at Shooter's Hill had ~ 1 163 vascular bundles. The average vascular bundle diameter and the area were ~ 0.03 mm and 42.4 mm^2, respectively. Approximately 128 mm^2 in the 680.78 mm^2 (44.9 mm culm diameter) was occupied by the vascular bundles. Most vascular bundles (73%) in the 6 mm thick wall were concentrated between the 2 and 5 mm depth zone (Plate 5-3). Vascular bundles were compacted towards the culm surface and dispersed deeper in the culm, which was important for identifying high sap flow regions within the culm.

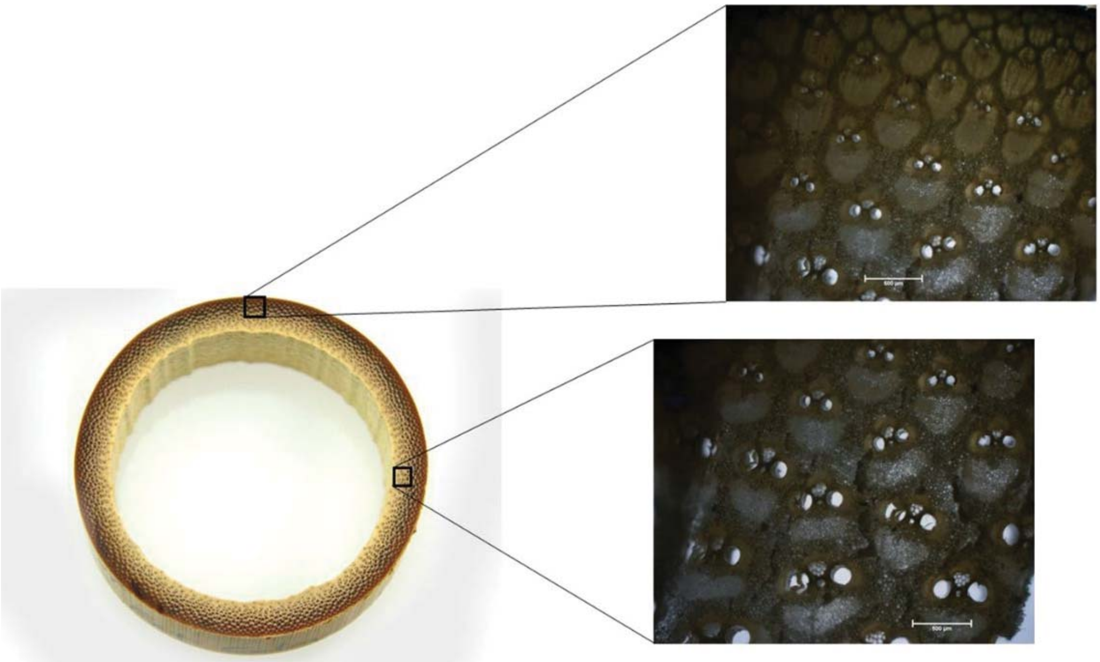


Plate 5-3: Cross-section of beema culm and vascular bundles distribution

The SEM-captured images showed three to four vascular bundles in the 1 x 1 mm^2 balcooa culm cross-section (Plate 5-4). The total number of vascular bundles in the 1 x 1 mm^2 area in both beema and balcooa were the same (Plate 5-5).

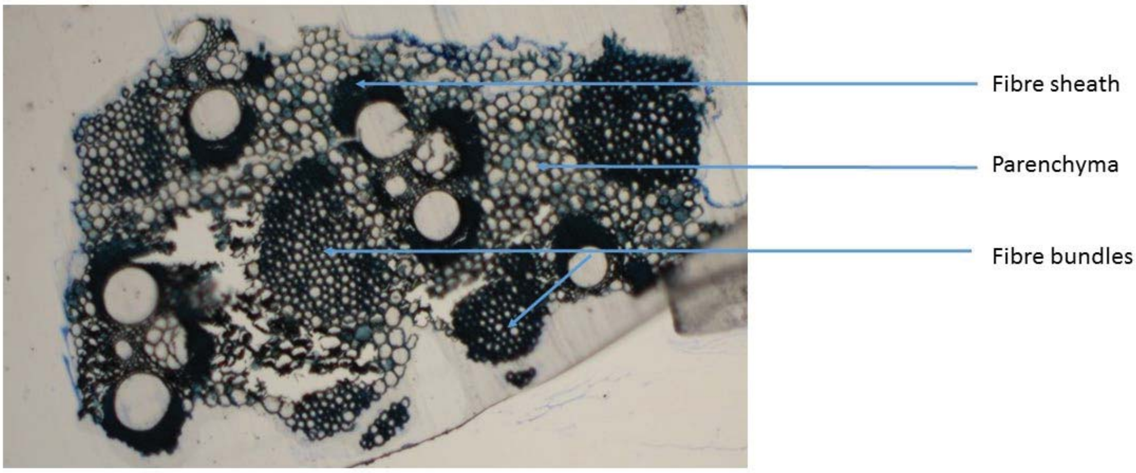


Plate 5-4: Balcooa bamboo culm cross-section

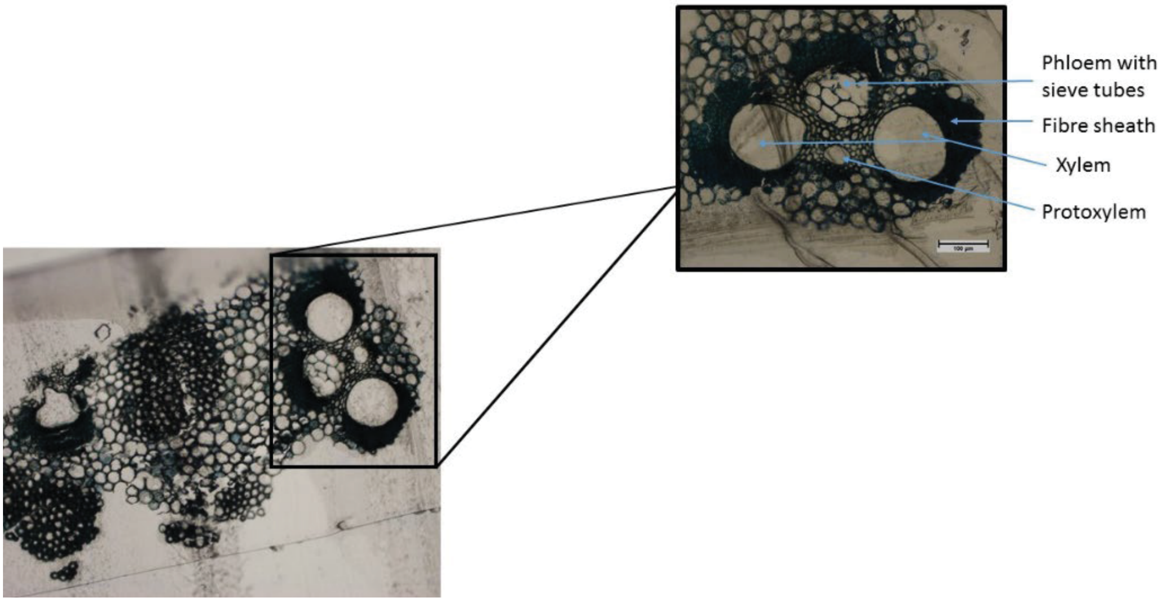


Plate 5-5: Balcooa bamboo vascular bundle structure

Approximately 33 balcooa vascular bundles were identified in the 20 mm^2 culm under the light microscope. Therefore, the 54.5 mm balcooa culm had at least 2 542 vascular bundles, of which 65% of the 5.3 mm thick culm were located within the 2 to 4.5 mm depth region (Plate 5-6). The average vascular bundle diameter and the area were ~ 0.03 mm and 42.4 mm^2, respectively. Approximately 562 mm^2 in the 1 848.8 mm^2 (54.5 mm culm diameter) were occupied by the vascular bundles.

An overall comparison of the anatomy of balcooa and beema indicated that balcooa had more vascular bundles per mm of culm (46.6) when compared to beema (25.9).

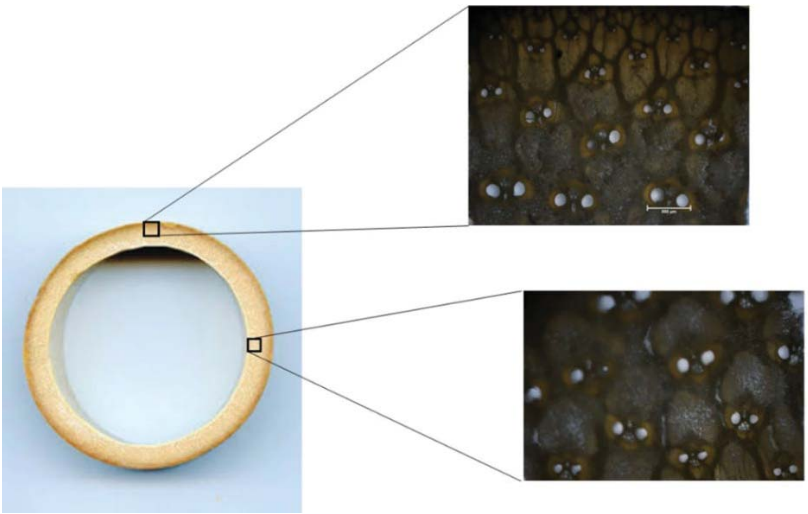


Plate 5-6: Cross-section of balcooa culm and vascular bundle distribution

5.1.5 Water use estimates using the HPV technique (KwaZulu-Natal)

Four beema culms were monitored from October 2018 to February 2020. The data was used to provide a combined water use estimate of the beema site based on the four culms monitored and the frequency size classes of all the culms (stand-scale transpiration) measured in the 10 m x 10 m plot. High daily sap flows, reaching 300 ℓ day^{-1}, were recorded on warmer days of summer for the beema plot (December to March), except on cool cloudy days when only ~ 170 ℓ day^{-1} were recorded (e.g. on 15 to 30 December 2018) (Figure 5-16). By contrast, consistently low sap flows < 150 ℓ day^{-1} were recorded in winter (May to July 2019) with a few warmer days reaching 170 ℓ day^{-1} in July 2019. Increasing sap flows from ~ 200 ℓ day^{-1} to > 300 ℓ day^{-1} were recorded from September 2019 to February 2020 (Figure 5-16).

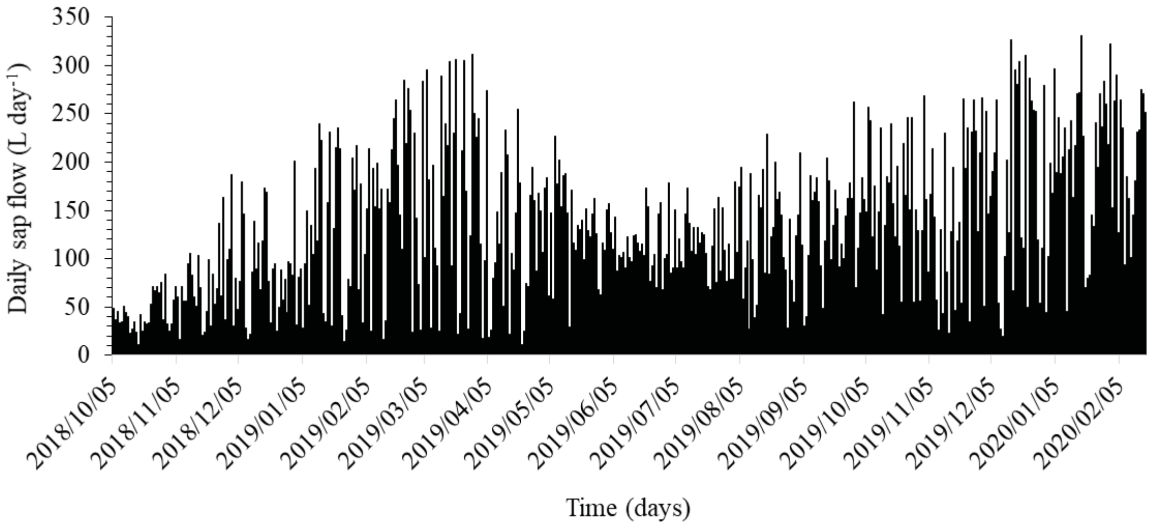


Figure 5-16: Total daily sap flow (ℓ day^{-1}) of the beema stand for different seasons at Shooter's Hill from 2018 to 2020

Daily water use (stand transpiration) was ~ 1.6 to 3.4 mm day^{-1} in summer (November 2018/19 to February 2019/20) with ~ 1.0 to 1.6 mm recorded in winter (May to July 2019) (Figure 5-17). For the 2018/19 hydrological year (12-month period from 1 October to 30 September), this resulted in an annual water use of ~ 422.1 mm year^{-1}.

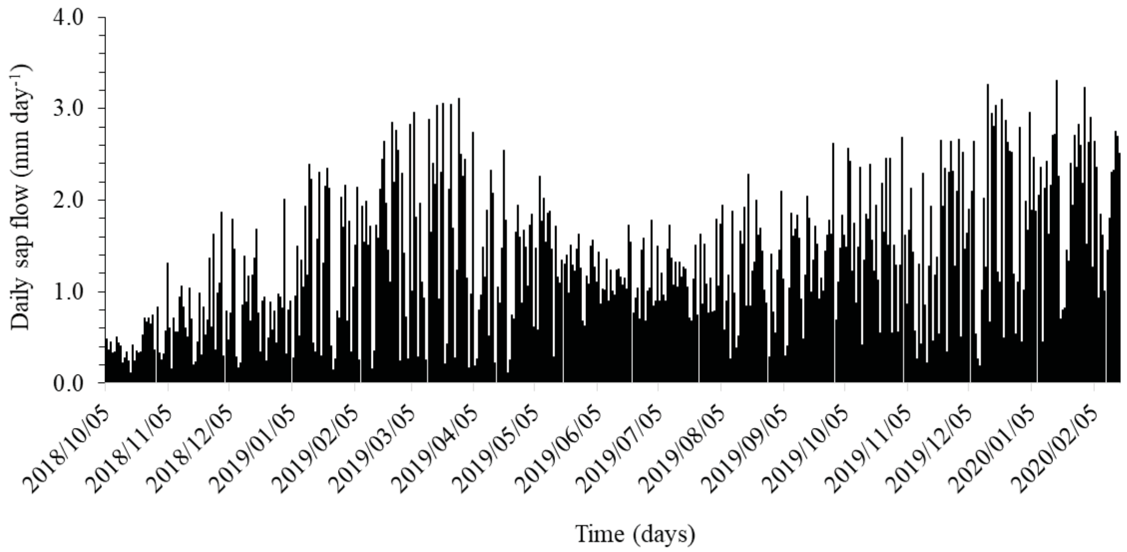


Figure 5-17: Total daily sap flow (mm day^{-1}) of the beema stand for different seasons at Shooter's Hill from 2018 to 2020

High water use > 2.0 mm day^{-1} was recorded in February 2019, when solar radiation, air temperature, daily total rainfall and relative humidity was 30 MJ (A), ~ 23 ^{o}C (B), > 15 mm (C) and > 90% (D), respectively (see Figure 5-18A–D). These high water-use rates were achieved when neither energy nor moisture were limiting transpiration.

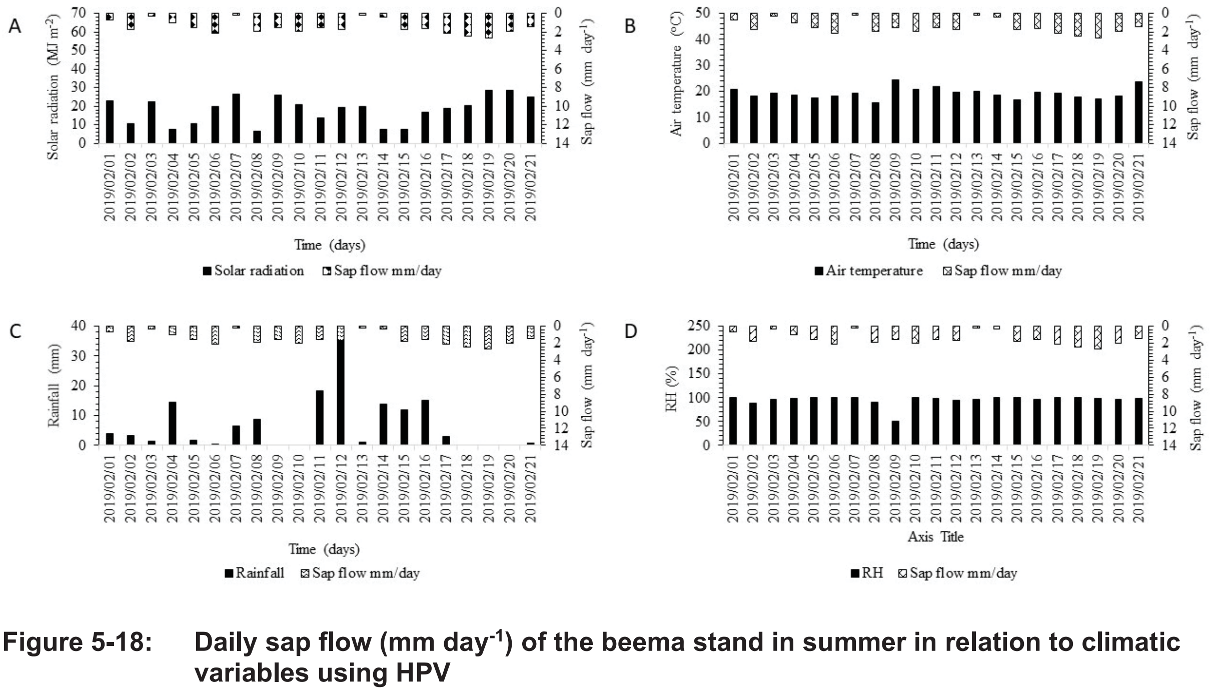


Figure 5-18: Daily sap flow (mm day^{-1}) of the beema stand in summer in relation to climatic variables using HPV

By contrast, water use in June 2019 during the dry winter in the beema plantation was low, only reaching ~ 1.5 mm day^{-1}. During this period, solar radiation, air temperature, rainfall and average relative humidity were ~ 12 MJ (A), 16 ^{o}C (B), ~ 3 mm (C) and < 80% (D), respectively (see Figure 5-19). Transpiration was consequently both energy and moisture limited.

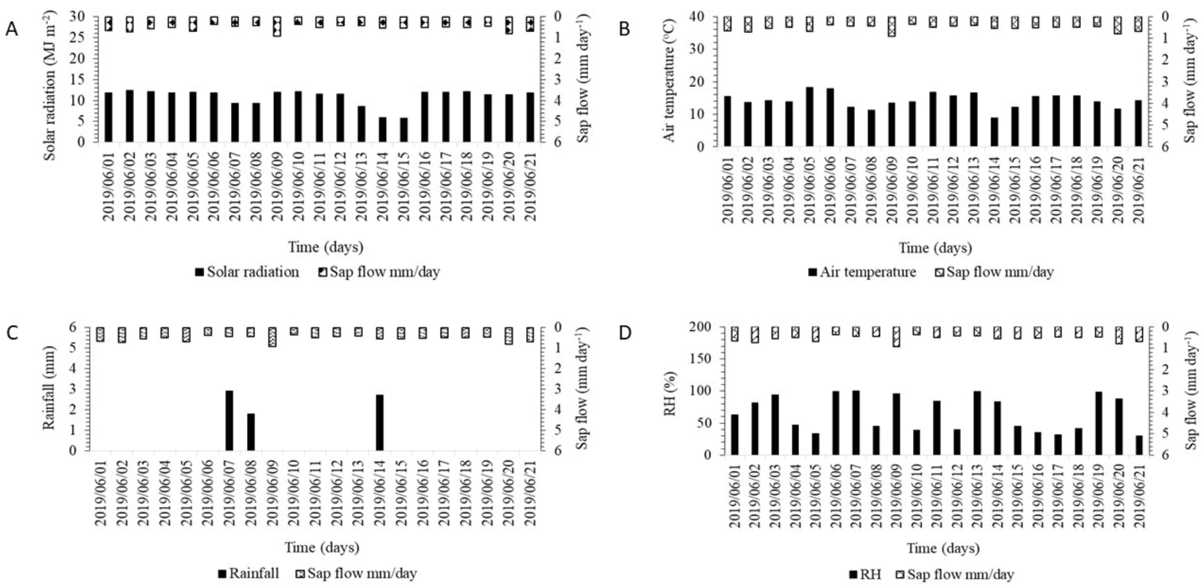


Figure 5-19: Daily sap flow (mm day^{-1}) of the beema stand in winter in relation to climatic variables using HPV

The water use of balcooa culms was recorded from January 2019 to February 2020. Plot or stand sap flows ≥ 150 ℓ day^{-1} were recorded in summer (January to March 2019) with a maximum sap flow of ~ 220 ℓ day^{-1} in February 2019 (Figure 5-20). Low plot sap flows of ≤ 70 ℓ day^{-1} were recorded in winter (May to July 2019) with the exception of 80 ℓ day^{-1}, which was recorded on the warmer days of 19 and 20 July 2019 (Figure 5-19). Increasing sap flows from ~ 100 ℓ day^{-1} to > 200 ℓ day^{-1} were recorded from September 2019 to January 2020 (Figure 5-20).

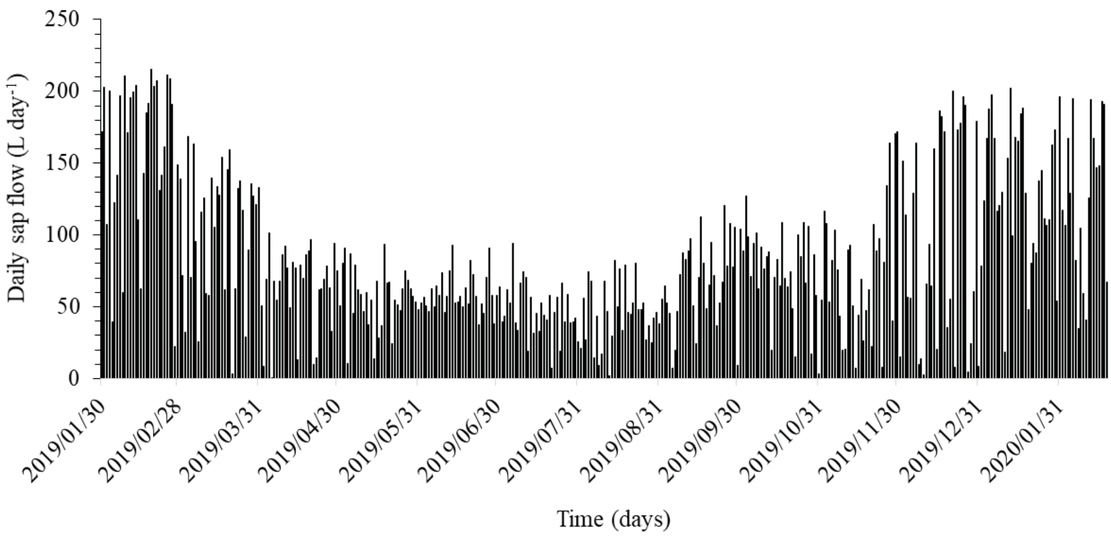


Figure 5-20: Total daily sap flow (ℓ day^{-1}) of the balcooa stand for different seasons at Shooter's Hill from 2018 to 2020

Using the size class data and a projected canopy area of 6 x 6 m (36 m^2), the daily transpiration was estimated to be ~ 3.8-5.6 mm day^{-1} in summer and ≤ 2.4 mm day^{-1} in winter (Figure 5-21).

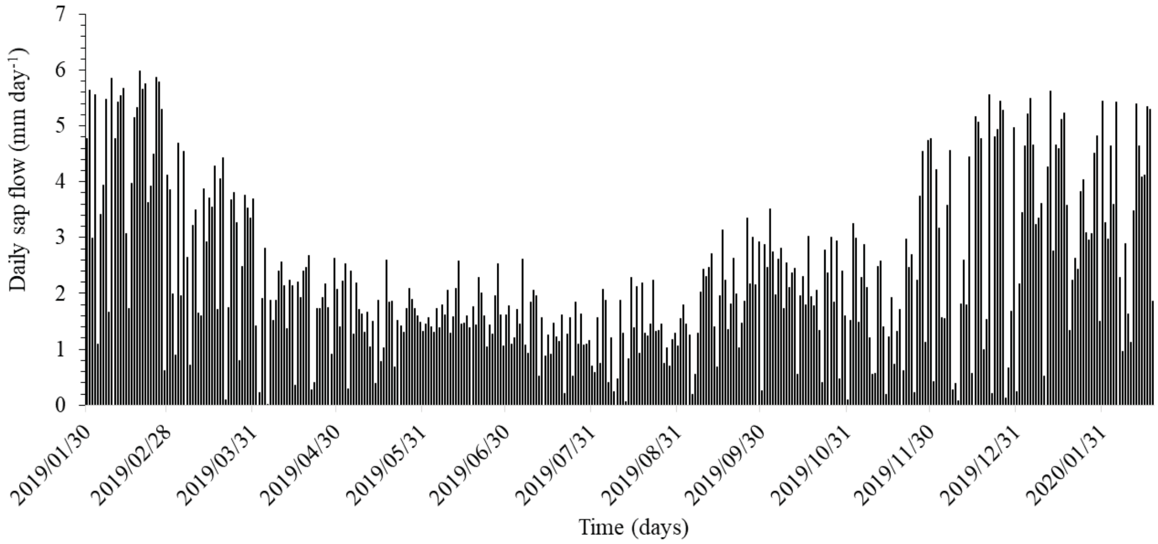


Figure 5-21: Total daily sap-flow (mm day^{-1}) of the balcooa stand for different seasons at Shooter's Hill from 2018 to 2020

When transpiration was not limited by either energy or moisture, high water use ~ 6.0 mm day^{-1} was recorded for the balcooa stand in February 2019. During this period, solar radiation, air temperature, rainfall and relative humidity recorded were 30 MJ (A), ~ 23 ^{o}C (B), > 15 mm (C) and > 90% (D), respectively (Figure 5-22A-D).

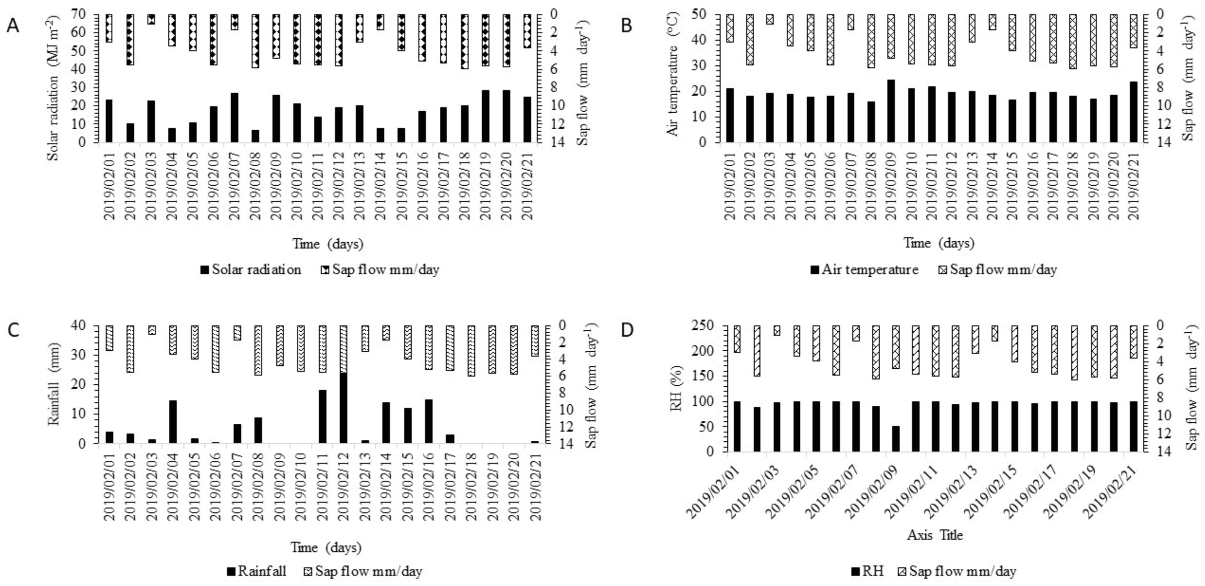


Figure 5-22: Daily sap flow (mm day^{-1}) of the balcooa stand in summer in relation to climatic variables using HPV

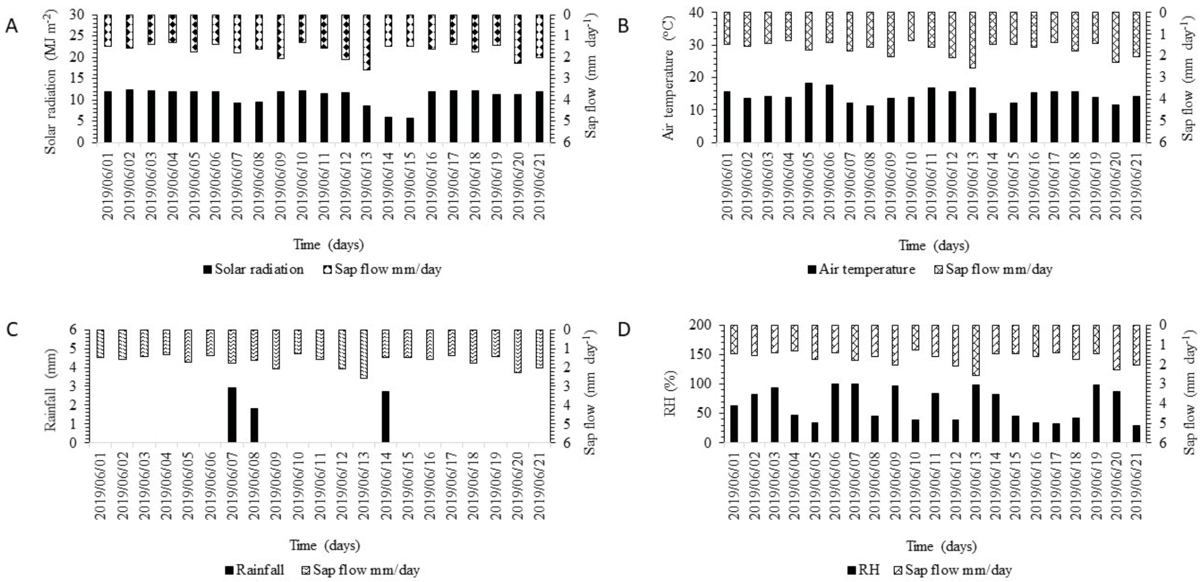


Figure 5-23: Daily sap flow (mm day^{-1}) of the balcooa stand in winter in relation to climatic variables using HPV

By contrast, low water use of ~ 2.3 mm day^{-1} was recorded in June 2019 when solar radiation, air temperature, rainfall and average relative humidity were ~ 12 MJ (A), 16 ^{o}C (B), ~ 3 mm (C) and < 80% (D), respectively (Figure 5-23 A-D). These low water use rates were as a result of both energy- and moisture-limiting transpiration.

Daily stand sap flow in the eucalyptus trees showed a high variation of between 700 and 310 ℓ day^{-1} in summer and winter, respectively (Figure 5-24). These results were based on a 10 x 10 m (100 m^{2}) plot.

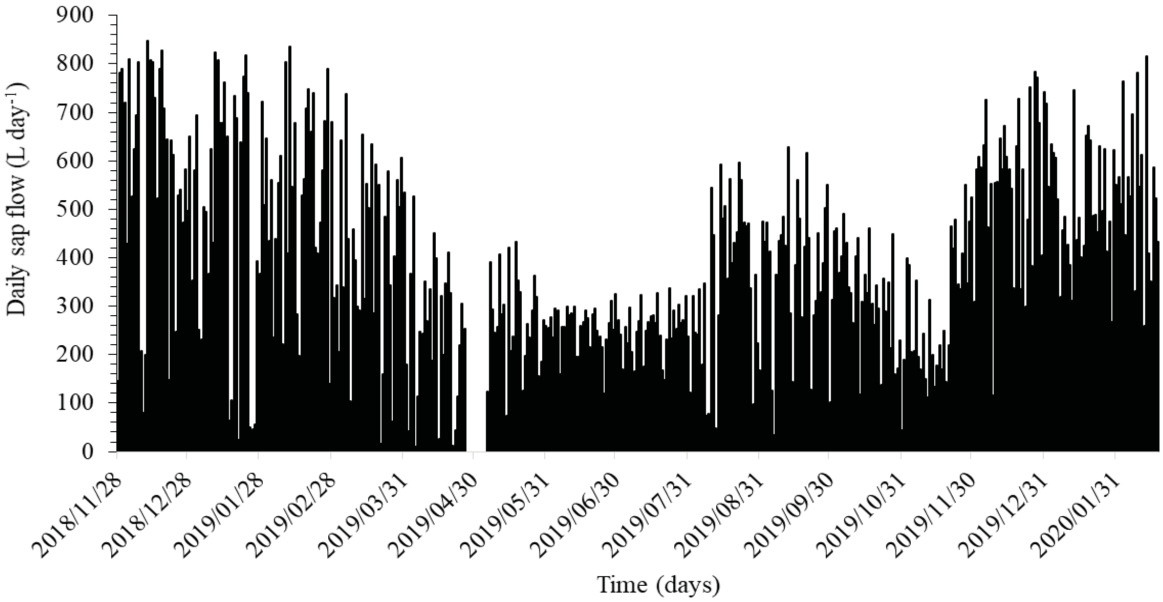


Figure 5-24: Seasonal daily sap flow (ℓ day^{-1}) at the eucalyptus plantation in Shooter's Hill from 2018 to 2020

This converts to a daily transpiration of 7.0 and 3.2 mm day^{-1} during summer and winter, respectively. From December 2018 to November 2019, the estimated total water use of the young eucalyptus trees was ~ 1 305.3 mm (Figure 5-25).

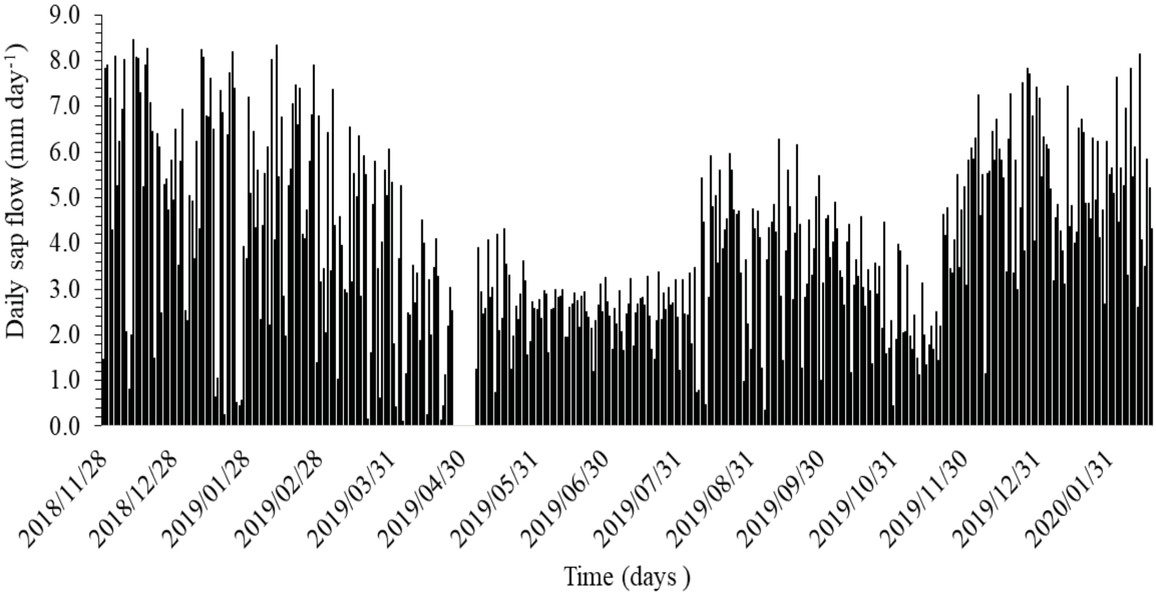


Figure 5-25: Seasonal daily transpiration (mm day^{-1}) of the eucalyptus plantation at Shooter's Hill from 2018 to 2020

High water use of ~ 7.0 mm day^{-1} was recorded in February 2019 when neither energy nor moisture were limiting transpiration. During this period, solar radiation, air temperature, rainfall and relative humidity were 30 MJ (A), 25 ^{o}C (B), > 15 mm (C) and ≥ 90% (D), respectively (Figure 5-26 A-D).

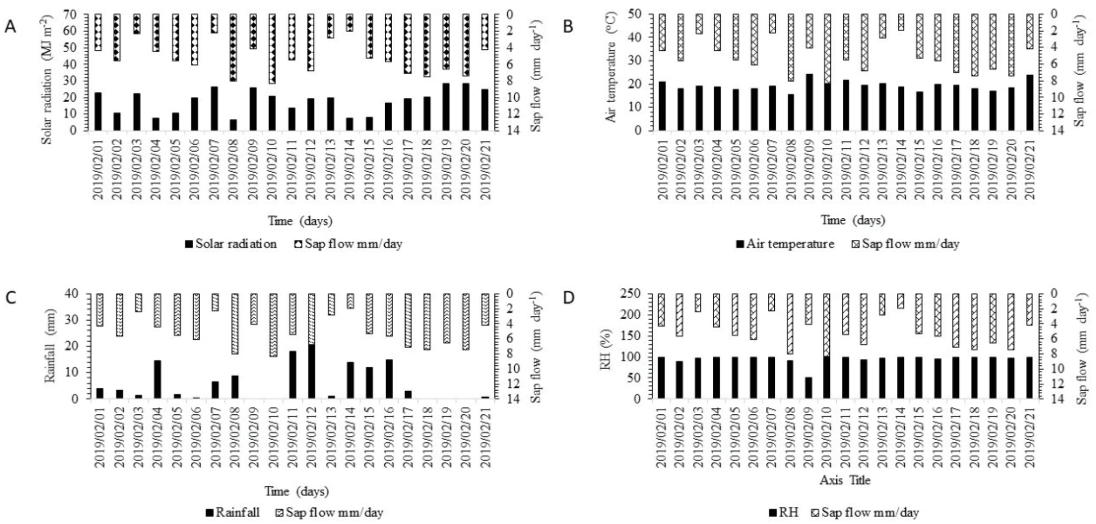


Figure 5-26: Daily sap flow (mm day^{-1}) of the eucalyptus trees in summer in relation to climatic variables using HPV

By contrast, low water use of ~ 3.0 mm day^{-1} was recorded in winter (June 2019) when solar radiation, air temperature, rainfall and average relative humidity were ~ 12 MJ (A), 16 ^{o}C (B), ~ 7 mm (C) and < 65% (D), respectively (Figure 5-27 A-D). Thus, similar to the other species studied, low water use rates were the result of limited transpiration through low energy and moisture.

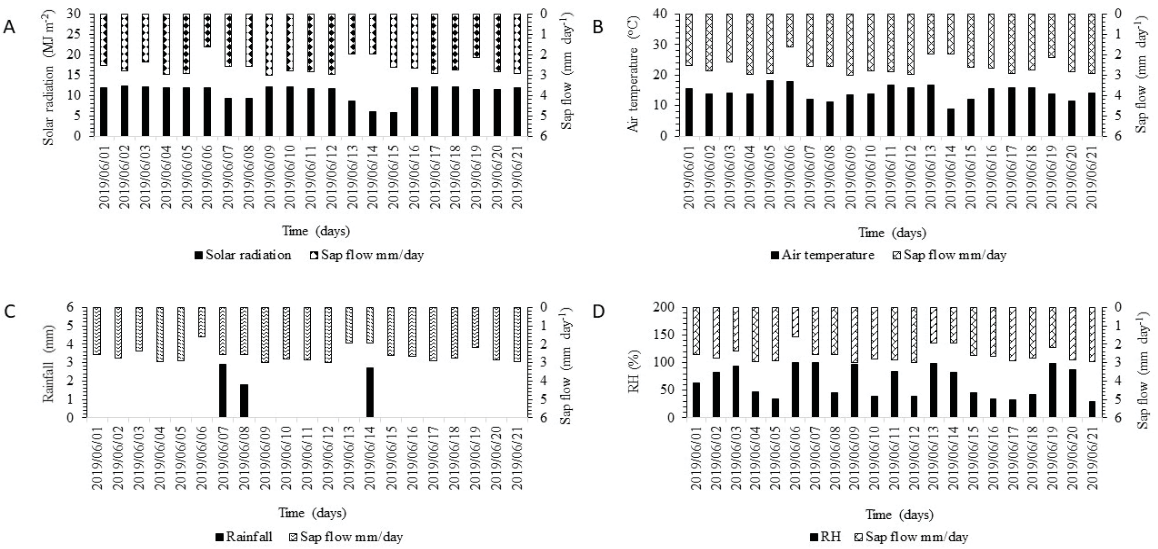


Figure 5-27: Daily sap flow (mm day-1) of the eucalyptus trees in winter in relation to climatic variables using HPV

Four black wattle trees were instrumented, measured and compared at the Shooter's Hill site. The integrated tree water use showed that these four trees were using ~ 15.0 to 23.0 ℓ day^{-1} in both winter and summer (Figure 5-28). This was based on a planting espacement of 3 x 1.5 m (4.5 m^2) and on the average projected canopy area of the trees.

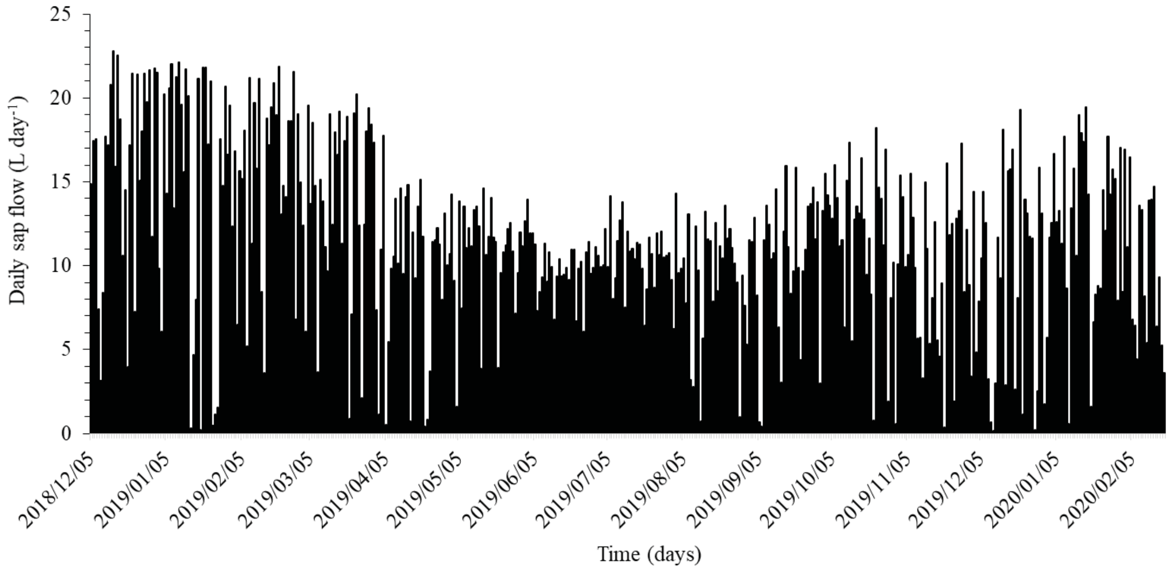


Figure 5-28: Seasonal sap flow (ℓ day-1) of the black wattle trees at Shooter's Hill from 2018 to 2020

This translated into ~ 4.0 to 5.0 mm day^{-1} in summer and 2.4 to 3.2 mm day^{-1} in winter (Figure 5-29).

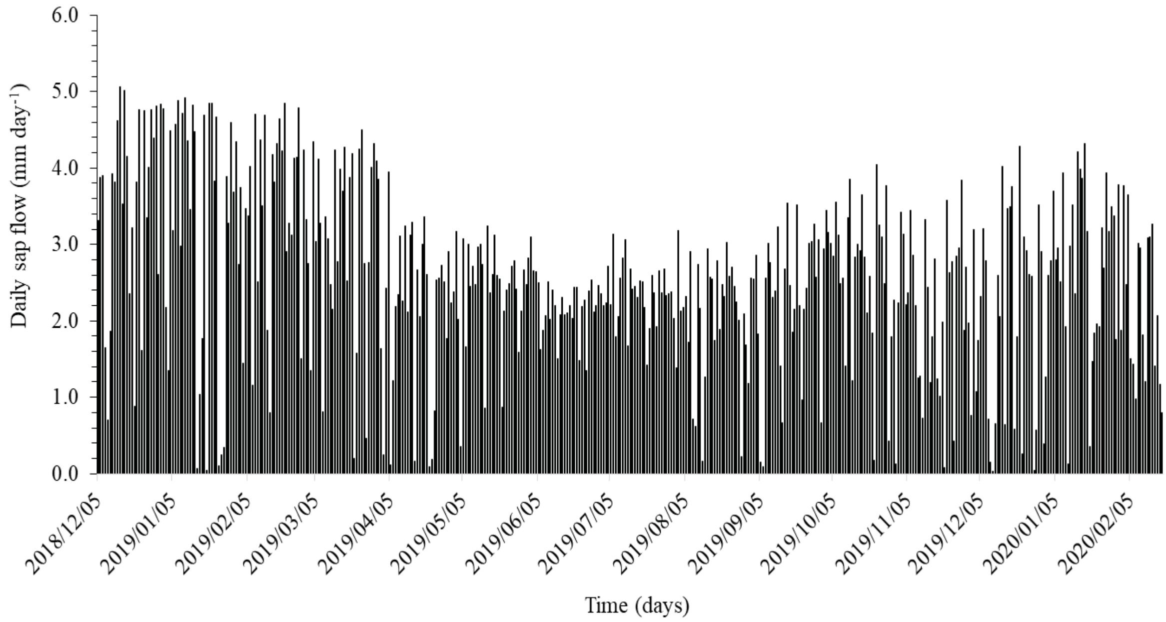


Figure 5-29: Daily transpiration (mm day^{-1}) of black wattle trees for different seasons at Shooter's Hill from 2018 to 2020

High water use (~ 5.0 mm day^{-1}) was recorded in January 2019 (summer) for the black wattle trees when solar radiation, air temperature, rainfall and relative humidity were 30 MJ (A), 25 ^{o}C (B), > 15 mm (C) and > 90% (D), respectively (Figure 5-30 A-D). These were achieved when neither energy nor moisture were limiting transpiration.

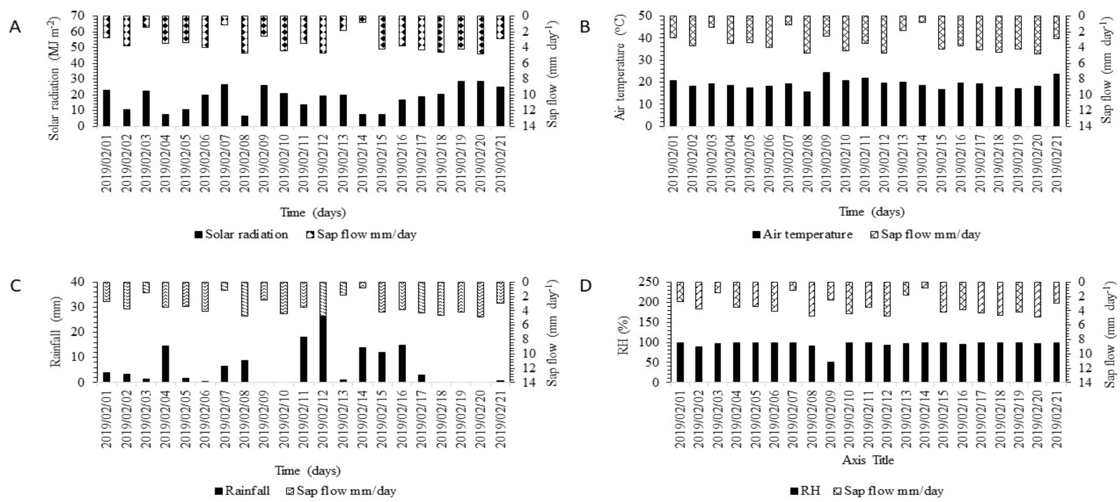


Figure 5-30: Daily sap flow (mm day^{-1}) of the black wattle trees in summer in relation to climatic variables using HPV

Low water use recorded in June 2019 (during winter), when transpiration was limited by energy and moisture, was ~ 2.5 mm day^{-1}. These values were in response to solar radiation, air temperature, rainfall and average relative humidity recorded to be ~ 12 MJ (A), 16 ^{o}C (B), ~ 7 mm (C) and < 65% (D), respectively (Figure 5-31 A-D).

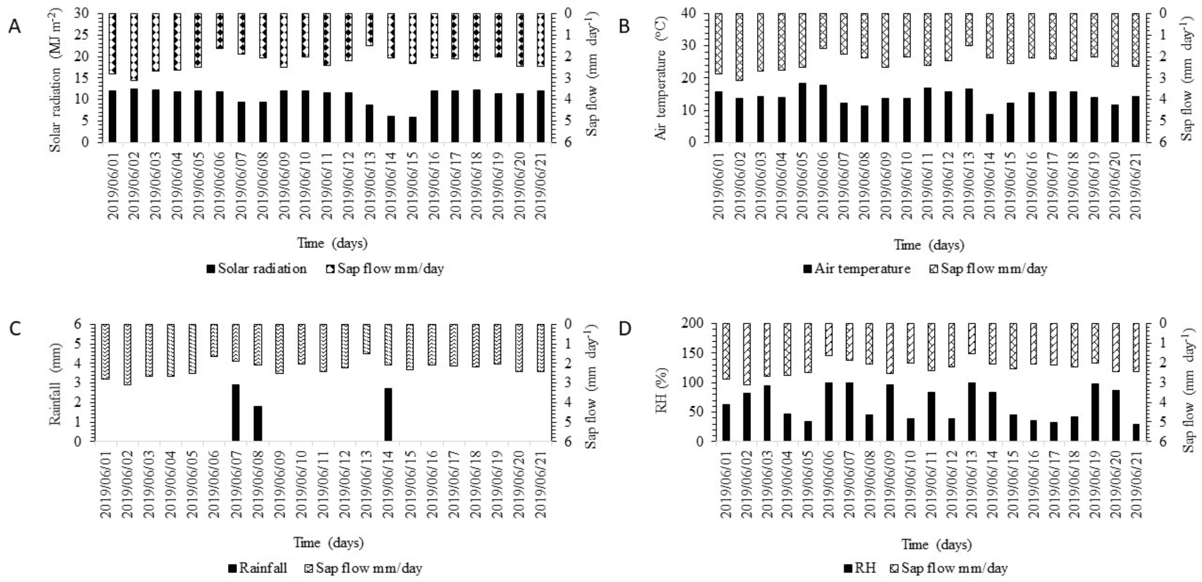


Figure 5-31: Daily sap flow (mm day^{-1}) of the black wattle trees in winter in relation to climatic variables using HPV

5.1.6 Water use estimated using stem steady state

Hourly and daily water use data was collected for the 25 and 50 mm beema culm diameters using SSS from September 2018 to January 2020 (Figure 5-32). The data was used to provide a combined water use estimate of the beema stand based on the six culms monitored and the frequency size classes of all the culms measured in the 10 x 10 m (100 m^2) plot.

Higher stand sap flows of > 250 ℓ day^{-1} were recorded in summer (November 2018 to March 2019), following low sap flows of ~ 190 ℓ day^{-1} in spring (September to October 2018) (Figure 5-32). By contrast, low sap flows of < 170 ℓ day^{-1} were recorded in winter (May to July 2019), with flows of approximately 190 ℓ day^{-1} in the fewer warmer days of winter (May and July 2019) (Figure 5-32). Increasing sap flows of > 200 ℓ day^{-1} were observed in the spring and summer season (September 2019 to January 2020), following low sap flows of ~ 80 ℓ day^{-1} were measured in July and August 2019, followed by higher levels in spring and summer recorded in September to December 2020 (Figure 5-32).

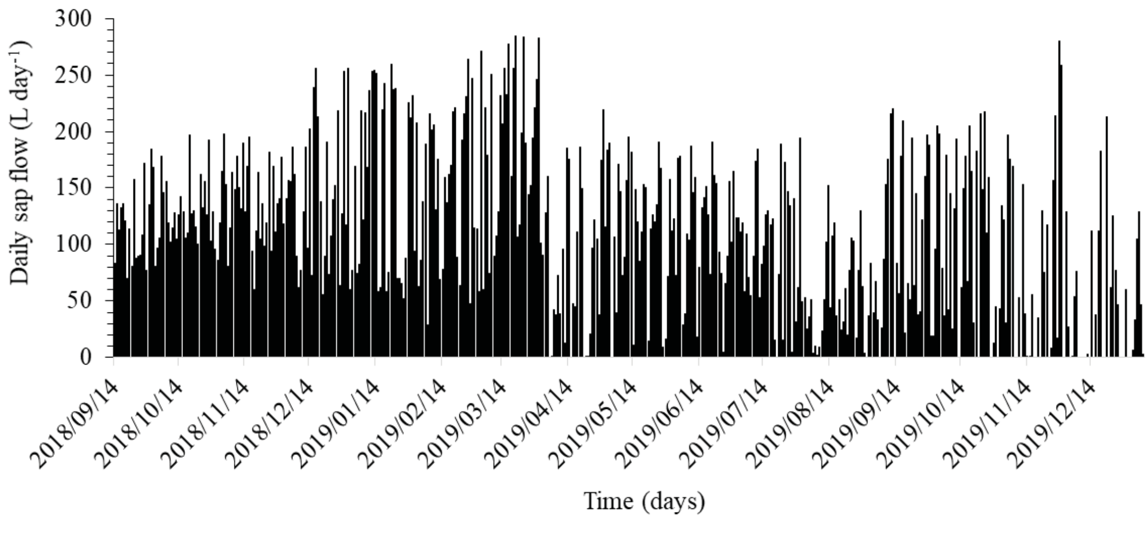


Figure 5-32: Seasonal daily sap flow (ℓ day^{-1}) of the beema stand at Shooter's Hill

Upscaling various size classes within the plot gave daily sap flow rates approaching 2.8 mm day^{-1} in summer and < 1.7 mm day^{-1} in winter (Figure 5-33). This resulted in an average transpiration rate of approximately 1.0 to 2.7 mm day^{-1} for the monitoring period of 17 months.

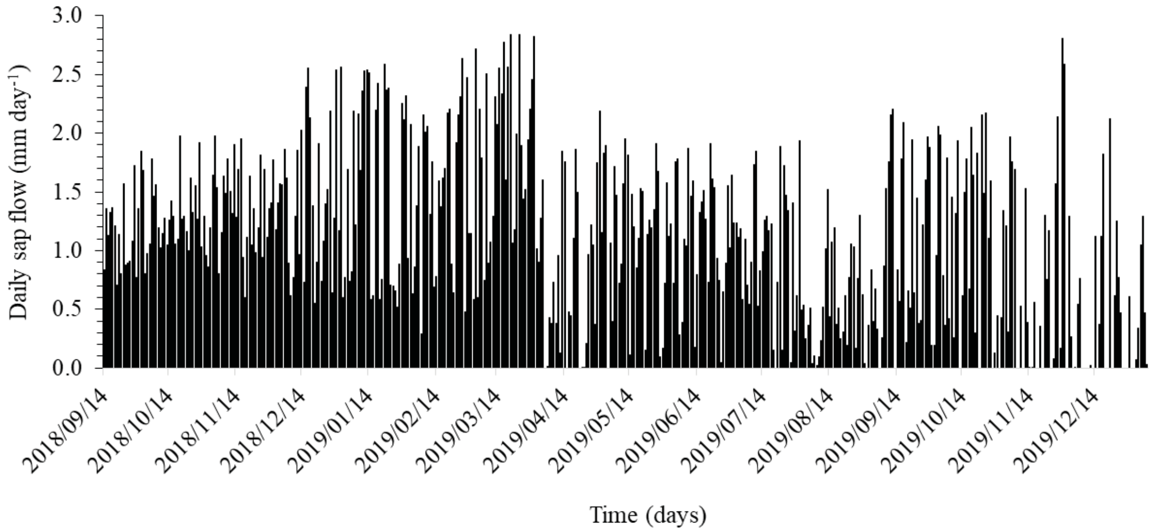


Figure 5-33: Daily transpiration (mm day^{-1}) of the beema stand for different seasons at Shooter's Hill

High water use (≥ 2.0 mm day^{-1}) was recorded in February 2019 (summer) using SSS at Shooter's Hill when maximum solar radiation, average air temperatures, total rainfall and relative humidity of ~ 30 MJ, ~ 26 °C, 66.8 mm and > 90%, respectively, were recorded (Figure 5-34 A-D).

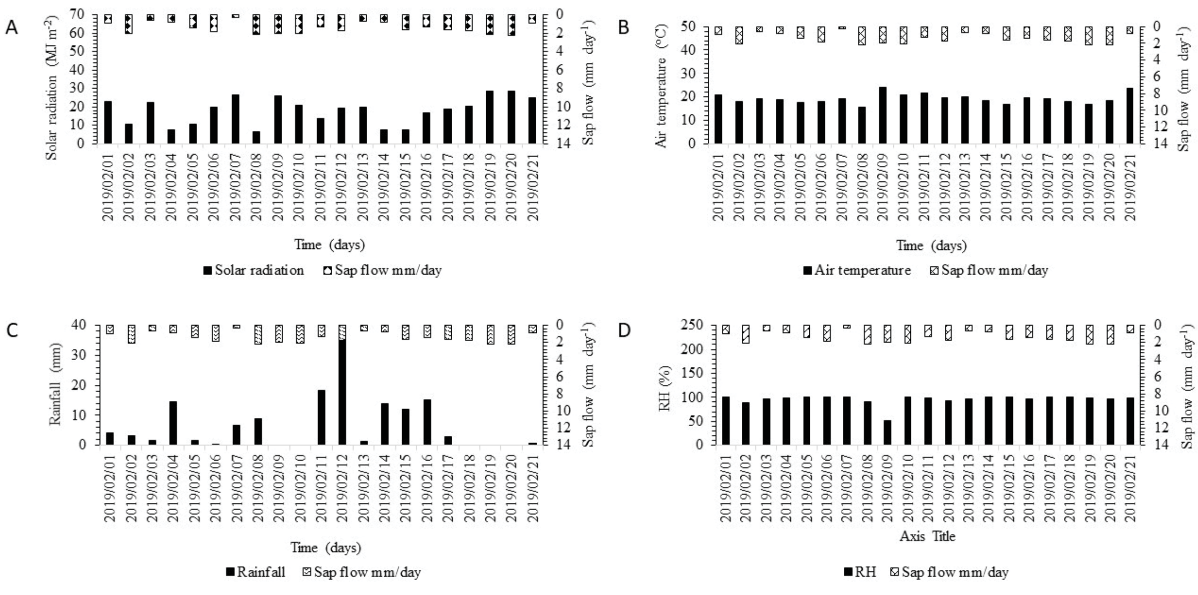


Figure 5-34: Daily sap flow (mm day^{-1}) of the beema stand in summer in relation to climatic variables using SSS

In the dry winter periods (June 2019), low water use (~ 1.5 mm day^{-1}) was recorded in the beema plantation at Shooter's Hill (Figure 5-35). Corresponding solar radiation, air temperatures and a low total rainfall of ~ 12 MJ, < 15 °C and 7.4 mm, respectively, were recorded.

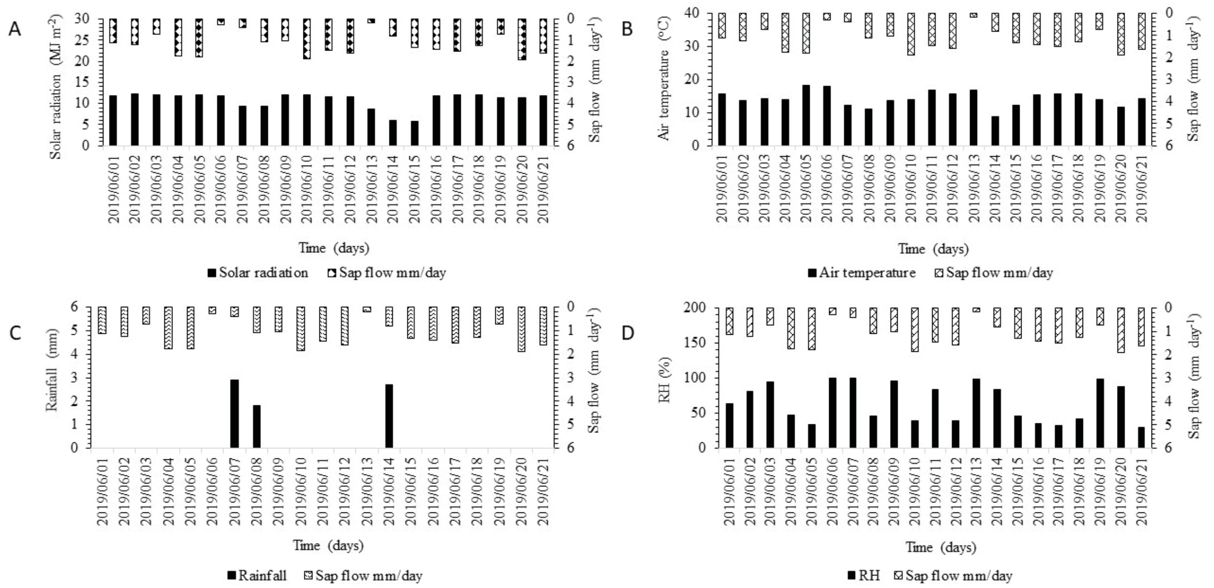


Figure 5-35: Daily sap flow (mm day^{-1}) of the beema stand in winter in relation to climatic variables using SSS

Hourly and daily water use for the 70 and 100 mm balcooa culms were monitored from September 2018 to January 2020. The data collected was used to provide a combined water use estimate for the balcooa plantation based on four culms monitored and the frequency size classes of all culms measured within the 6 x 6 m (36 m^2) plot.

Sap flow reaching 250 ℓ day^{-1} was recorded in February 2019 (summer), following flows ~ 200 ℓ day^{-1} in January 2019 (Figure 5-36). Low winter sap flows recorded in June and July 2019 were 70 ℓ day^{-1}, with a minimum flow of < 10 ℓ day^{-1} recorded in the dry winter season in August and September 2019. Nevertheless, increasing sap flows were recorded at the beginning of September 2019 (spring) to January 2020 (summer), with the highest sap flow of 230 ℓ day^{-1} recorded in December 2019 (Figure 5-36).

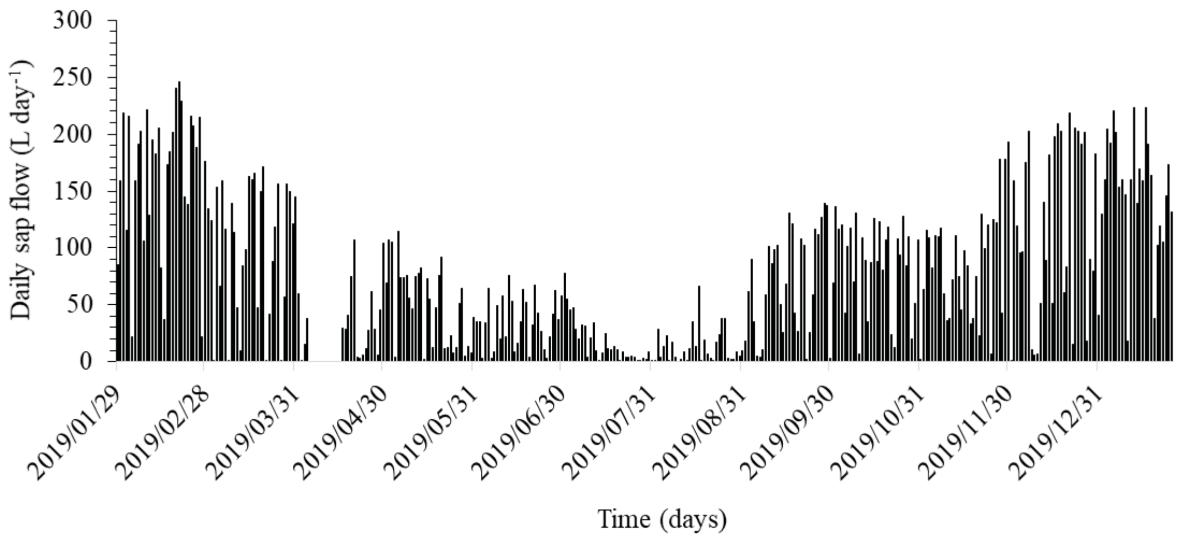


Figure 5-36: Seasonal daily sap flow (ℓ day^{-1}) of the balcooa stand at Shooter's Hill

Upscaling various size classes within the plot gave daily sap flow rates approaching 6.5 mm day^{-1} in summer and < 2.5 mm day^{-1} in winter (Figure 5-37). This gave an average transpiration rate of approximately 0.5 to 6.5 mm day^{-1} for the monitoring period of 17 months.

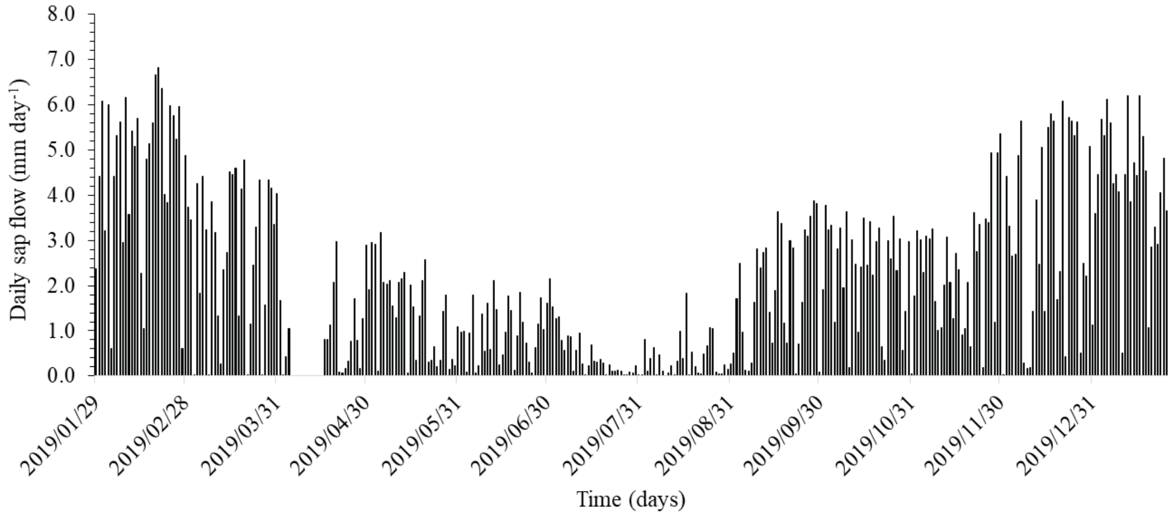


Figure 5-37: Total daily sap flow (mm day^{-1}) of the balcooa stand for different seasons at Shooter's Hill

High summer water use (> 7.0 mm day^{-1}) was recorded in February 2019 at the balcooa site (Figure 5-38), when maximum solar radiation, air temperature and rainfall were recorded. Transpiration was not limited by moisture and energy.

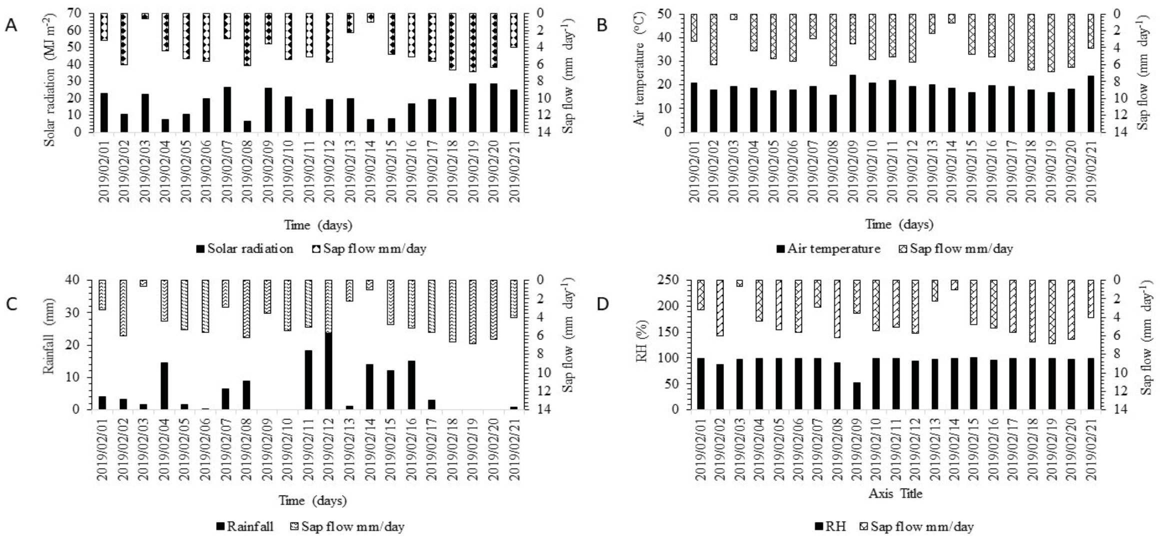


Figure 5-38: Daily sap flow (mm day^{-1}) of the balcooa stand in summer in relation to climatic variables using SSS

In contrast, low water use (< 2.0 mm day^{-1}) was recorded in winter, when transpiration was limited by moisture and energy (Figure 5-39).

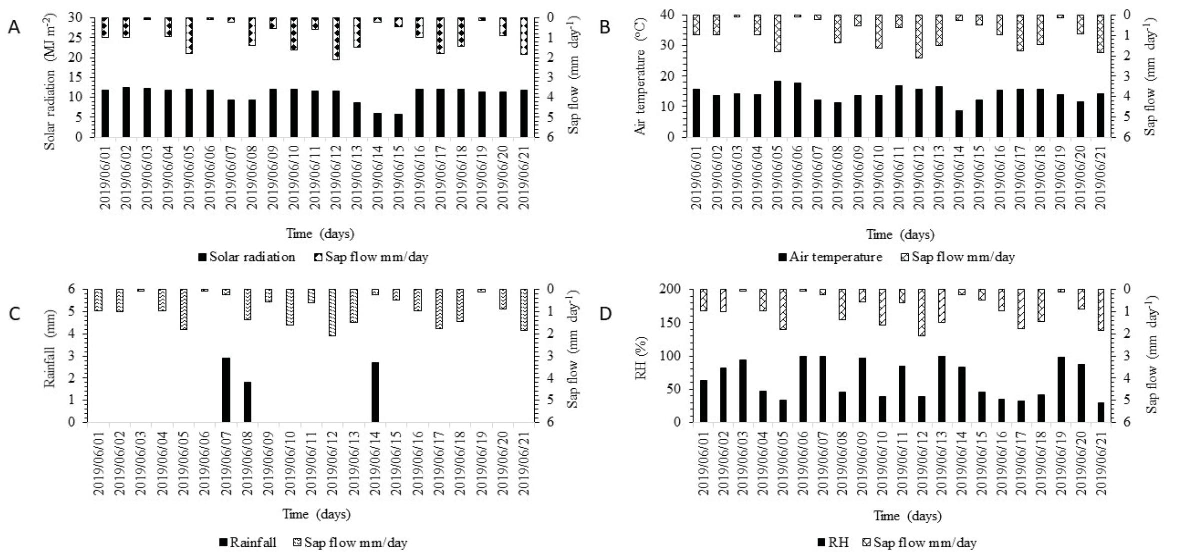


Figure 5-39: Daily sap flow (mm day^{-1}) of the balcooa stand in winter in relation to climatic variables using SSS

5.1.7 Total water use of the beema, balcooa, eucalyptus and black wattle at Shooter's Hill

Annual water use of beema, balcooa, eucalyptus and black wattle trees were calculated from January 2019 to December 2019 (a 12-month period) using HPV and SSS. The highest water use using the SSS technique (~ 1 301.2 mm) was recorded at the eucalyptus plantation, followed by 911.4 mm recorded from the black wattle trees using HPV (Table 5-4). Bamboo had a low water use compared to other land uses, both in the balcooa and beema plantations, of 746.1 and 509.7 mm, respectively. The total water use of balcooa was 141.6 mm higher at the end of the 12-month period (Table 5-4). Although there were fewer balcooa culms (72) compared to beema culms (215), they had significantly higher culm diameters, with 56% of the balcooa culms falling into the 30–49 mm size class. The higher number of vascular bundles per mm of balcooa culm (46.6), compared to bema culm (25.9), together with the higher culm diameters, would contribute to the higher water use.

Table 5-4: Total water use of beema, balcooa, eucalyptus and black wattle trees from 1 January 2019 to 31 December 2019 using HPV and SSS. It is important to note that converting to mm year^{-1} normalises the different site stand areas.

	Total sap flow (mm year^{-1})		
Species name	**HPV**	**SSS**	**Area measured (m^2)**
Beema	509.7	392.1	100
Balcooa	746.1	651.3	36
Eucalyptus	1301.2		100
Wattle	911.4		18

The corresponding grass reference evaporation (ET_0) was measured to calculate monthly crop factors (K_c) and the average seasonal K_c. In summer, ET_0 reached 89.55 mm (March 2019), and – as expected – was higher than the average transpiration of the balcooa and beema plantations of 88.61 mm and 55.24 mm, respectively (Table 5-5). Transpiration in the eucalyptus and black wattle sites of 129.20 mm and 96.37, respectively, were recorded in the same period.

The monthly ET_0 rates measured in summer were > 80 mm with maximum ET_0 reaching ~ 110 mm in December 2019 (Table 5-5). This showed that the summer ET_0 rates were high, unlike in the dry winter months (May to June 2019), when low ET_0 rates < 60 mm were measured (Table 5-5).

The lower K_c values recorded in beema (0.3 to 0.71) and balcooa (0.28 to 1.4), compared to eucalyptus (1.03 to 1.80) and black wattle (0.52 to 1.47) (Table 5-5) indicated that bamboo is a more conservative water user than these species. In the beema and balcooa culms, the highest K_c values were recorded in the wet summer, compared to the low values < 0.7 recorded in the dry winter (Figure 5-40).

Table 5-5: Comparison of the water use for different land-uses and ET_0 at Shooter's Hill (* = no data available)

Time (months)	Water use (mm month^{-1})										
			HPV		SSS		ET_0			Crop factor (K_c)	
	Beema	Balcooa	Eucalyptus	Wattle	Beema	Balcooa	(mm)	Beema	Balcooa	Eucalyptus	Wattle
October 2018	11.79	18.78	*	*	40.64	34.15	93	0.28	0.28	*	*
November 2018	21.07	36.21	*	*	40.92	89.11	96.1	0.32	0.65	*	*
December 2018	26.49	19.55	122.45	95.60	44.48	199.02	130.2	0.27	0.84	0.94	0.73
January 2019	38.56	40.17	106.76	101.48	49.02	*	117.8	0.37	*	0.91	0.86
February 2019	44.89	82.07	103.68	96.58	42.98	129.07	92.8	0.47	0.88	1.12	1.04
March 2019	53.37	90.00	89.72	96.37	57.11	87.21	108.5	0.51	0.82	0.83	0.89
April 2019	35.71	52.19	43.80	63.49	24.58	19.25	75.0	0.40	0.48	0.58	0.85
May 2019	41.35	48.35	48.78	74.02	35.50	43.50	58	0.66	0.79	0.84	1.28
June 2019	34.66	49.37	53.30	66.60	34.12	29.00	62	0.55	0.63	0.86	1.07
July 2019	35.69	40.45	54.27	72.89	31.26	14.66	58.9	0.57	0.47	0.92	1.24
August 2019	37.34	38.49	74.94	62.98	16.42	11.32	77.5	0.35	0.32	0.97	0.81
September 2019	41.13	55.44	79.13	67.96	29.71	57.43	108.5	0.33	0.52	0.73	0.63
October 2019	48.62	64.87	68.66	80.19	33.01	72.57	105.4	0.39	0.65	0.65	0.76
November 2019	45.04	62.54	60.95	66.62	24.64	74.78	120.9	0.29	0.57	0.50	0.55
December 2019	53.40	82.48	119.62	62.25	13.18	99.69	111.6	0.30	0.82	1.07	0.56
January 2020	63.48	114.04	111.03	85.98	*	106.47	124	0.51	0.89	0.90	0.69
February 2020	34.58	63.02	67.52	39.58	*	*	102.3	0.34	0.62	0.66	0.39

* = No data available

In the eucalyptus plantation, K_c values were high in both the dry winter and the wet summer, with values ranging from 1.3 to 1.8 (Figure 5-40). In the black wattle trees, K_c values reached a maximum of 1.47 in winter, whereas, in summer, K_c values < 0.98 were recorded (Figure 5-40).

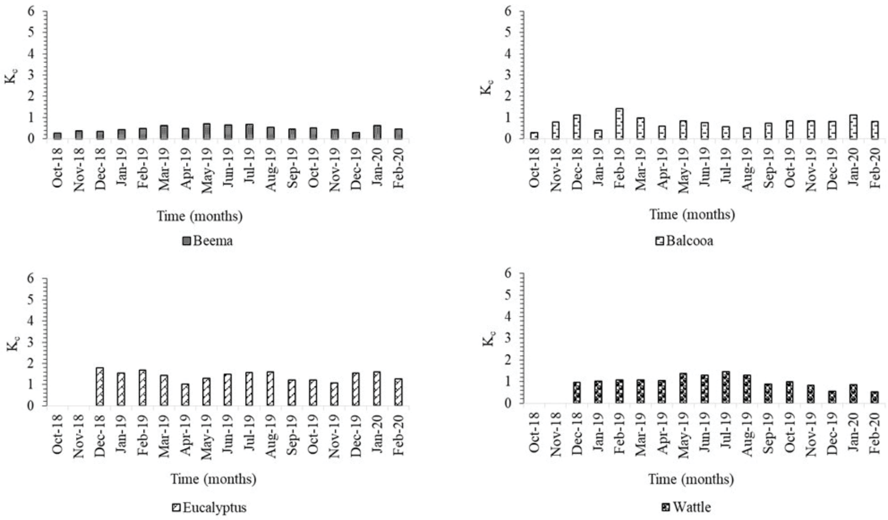


Figure 5-40: Monthly K_c values for the different land uses at Shooter's Hill

5.1.8 Comparison of SSS and HPV

The bamboo water use data for a three-month period was compared (January to March 2019) using HPV and SSS. Data was selected from the culms, where both systems were installed and in good working order to minimise bias. A strong positive correlation was observed for the balcooa (R^2 = 0.78) and the beema plantations (R^2 = 0.87) (Figure 5-41 A and B). This showed that the unaccounted for variation was < 20% for both systems. Since the SSS technique is regarded as a complete measure of water use, the high correlation indicates the reliability of using HPV to determine water use in bamboo.

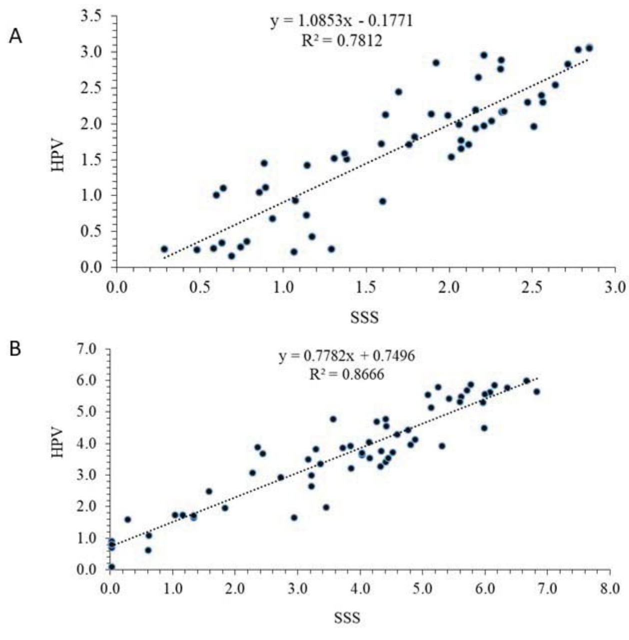


Figure 5-41: Regression analysis of daily transpiration of beema (A) and balcooa (B) culms using HPV and SSS

5.2 SURFACE RENEWAL (GRASSLAND TOTAL EVAPORATION)

5.2.1 Surface renewal calibration

The application of the surface renewal (SR) method requires the determination of the calibration constant alpha (α). This is achieved by using a direct measure of evapotranspiration measurement such as eddy covariance (EC). In our case, the decision was made to use an Applied Technologies Inc. (ATI) Model SATI/3Vx-Type sonic anemometer. This instrument was chosen as it has a high frequency serial output, which is suitable for interfacing with a CR1000 Campbell Scientific datalogger. Initially, the instrument was installed at Kowie Bamboo Farm near Bathurst. However, the data quality was poor due to frequent skipped scans. The instrument was eventually returned to Pietermaritzburg for testing. The project team could not resolve this problem and the instrument was sent back to the manufacturer in the USA for testing. This required the team to obtain an import/export licence, which caused considerable delays before it could be shipped. Unfortunately, the manufacturer also unable to resolve the problem and it was decided to upgrade the instrument with new electronics and software.

On its return, the instrument was interfaced with the datalogger through a serial interface by writing project-specific eddy covariance programs to determine the sensible heat flux (H) from both the ATI sonic-derived temperature (H_s) and a Chromel/Constantan fine wire thermocouple (H_{fw}). Output settings on the ATI sonic, programmed through Terra Term terminal emulation software were as follows:

Output settings

- Baud rate: 9 600
- Parity: Even
- Data bits: 7; stop bits = 1; flow control = none
- Outputs: U, V and W
- Output format: Ascii
- Data average: 20
- Orientation: Orthogonal
- Data output rate: 10 Hz (ten samples per second)

Options

- Output: RS232
- Data format: Terse mode
- LV304: 2D level accelerometer

A CRBasic program for the CR1000 was developed to input the serial output of the sonic using the SerialIn and SerialOpen commands and store the high frequency (HF) sonic and temperature data (Table 5-6). Each 30-minute period therefore contained 18 000 lines of data. The program then computed the 21 covariances from the HF data (Table 5-7) to compute the H_s and H_{fw} (Table 5-7) into 30-minute averages of H_s and H_{fw} (Table 5-8).

Table 5-6: One second of high frequency (10 Hz) Eastern Cape data

TOA5	8082	CR1000	8082	CR1000.St	CPU:2020(	12477	ts_data		
TIMESTAMP	RECORD	Uu	Uv	Uw	Ts	Tfw	actual_P	actual_R	diag_sonic
TS	RN	m/s	m/s	m/s	C	C	Degrees	Degrees	arb
		Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp
25:38.1	2508612	0.01	0	-0.02	27.65	25.64611	0.5	0.2	35
25:38.2	2508613	0	0	-0.02	27.65	25.70123	0.5	0.1	35
25:38.3	2508614	0	0	-0.02	27.65	25.64611	0.4	0.2	35
25:38.4	2508615	0	0	-0.02	27.65	25.64611	0.3	0.1	35
25:38.5	2508616	0	0	-0.02	27.65	25.64611	0.4	0	35
25:38.6	2508617	0	0	-0.02	27.65	25.64611	0.5	0	35
25:38.7	2508618	0.01	0	-0.02	27.65	25.64611	0.5	0.1	35
25:38.8	2508619	0.01	0	-0.02	27.65	25.64611	0.5	0.2	35
25:38.9	2508620	0.01	0	-0.02	27.65	25.64611	0.5	0.1	35

Table 5-7: An example of ten 30-minute time outputs of the 21 covariances and other variables output by the datalogger

TOA5	8082	CR1000	8082	CR1000.S	CPU:2020C	12477	COV30MIN																										
TIMESTAMP	RECOI	Uu_Avg	Uv_Avg	Uw_Avg	u_hor2_S_	theta2_D1	theta2_SD1_	CVu_u	CVu_v	CVu_Uhor	CVu_w	CVu_Ts	CVu_Tfw	CVv_v	CVv_Uhc	CVv_w	CVv_Ts	CVv_Tfw	CVUhor_U	CVUhor_w	CVUhor_T	CVUhor_	CVw_w	CVw_Ts	CVw_Tfv	CVTs_Ts	CVTs_Tfw	CVTfw_Tfw	Uu_Std	Uv_Std	Ts_Std	Ts_Avg	Tfw_Avg
TS	RN	m/s	m/s	m/s		Deg	Deg																						m/s	m/s	C	C	C
		Avg	Avg	Avg	WVc	WVc	WVc	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Cov	Std	Std	Std	Avg	Avg
2020/01/31 10:30	1	-0.0477	-0.0608	-0.0005	0.1107	223.0701	59.4719	0.0046	0.0007	-0.0025	-0.0005	0.0139	0.0048	0.0078	-0.0056	-0.0022	-0.0139	-0.0146	0.0061	0.0019	0.0034	0.0102	0.0049	0.0029	0.0112	0.7684	0.4888	0.5021	0.0675	0.0883	0.8766	22.3052	21.3442
2020/01/31 11:00	2	-0.0517	-0.0555	0.0004	0.1076	220.0840	56.7662	0.0042	0.0005	-0.0025	-0.0003	0.0108	0.0021	0.0069	-0.0044	-0.0021	-0.0124	-0.0134	0.0052	0.0017	0.0023	0.0086	0.0052	0.0062	0.0110	0.5889	0.3367	0.3178	0.0648	0.0829	0.7674	22.2976	21.1441
2020/01/31 11:30	3	-0.0439	-0.0510	0.0006	0.0996	222.0108	60.7931	0.0038	0.0007	-0.0022	-0.0005	0.0136	0.0067	0.0062	-0.0041	-0.0020	-0.0158	-0.0101	0.0047	0.0016	0.0027	0.0042	0.0039	0.0063	0.0095	1.6996	1.0368	0.7645	0.0619	0.0790	1.3037	23.4322	21.8341
2020/01/31 12:00	4	-0.0494	-0.0556	0.0000	0.1086	217.4815	58.7300	0.0041	0.0005	-0.0022	-0.0005	0.0177	0.0082	0.0077	-0.0051	-0.0022	-0.0137	-0.0102	0.0055	0.0017	0.0012	0.0040	0.0045	-0.0021	0.0047	0.3379	0.1726	0.1949	0.0640	0.0875	0.5813	23.5328	21.9835
2020/01/31 12:30	5	0.0093	0.0121	-0.0019	0.0322	54.0053	58.4954	0.0007	0.0001	-0.0001	0.0001	0.0118	0.0095	0.0006	-0.0002	0.0000	0.0070	0.0053	0.0004	0.0000	-0.0085	-0.0071	0.0003	0.0010	0.0013	0.8540	0.6473	0.7632	0.0260	0.0238	0.9241	25.7211	24.0225
2020/01/31 13:00	6	0.0152	0.0147	-0.0038	0.0291	47.3902	46.5065	0.0004	-0.0001	0.0001	0.0001	######	0.0006	0.0002	0.0001	0.0000	-0.0001	-0.0011	0.0002	0.0000	0.0000	0.0009	0.0002	0.0001	0.0007	0.0381	0.0452	0.2156	0.0194	0.0141	0.1951	26.6669	24.6925
2020/01/31 13:30	7	0.0072	0.0149	-0.0080	0.0272	69.1296	55.7683	0.0004	-0.0001	0.0001	0.0001	0.0001	0.0011	0.0003	0.0000	0.0000	-0.0002	-0.0021	0.0002	0.0000	0.0009	0.0016	0.0003	-0.0004	0.0001	0.0508	0.0580	0.2166	0.0205	0.0160	0.2253	26.8824	24.9316
2020/01/31 14:00	8	0.0033	0.0229	-0.0043	0.0258	83.8901	29.4390	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000	-0.0005	0.0001	0.0000	0.0001	0.0002	0.0001	-0.0001	-0.0004	0.0027	0.0023	0.0593	0.0096	0.0115	0.0516	26.3946	24.5212
2020/01/31 14:30	9	-0.0616	-0.0433	-0.0011	0.1106	206.4118	55.6904	0.0046	-0.0004	-0.0020	0.0000	0.0211	0.0114	0.0065	-0.0035	-0.0020	-0.0071	-0.0066	0.0046	0.0011	-0.0025	0.0025	0.0047	0.0099	0.0104	1.4235	0.9584	0.7839	0.0680	0.0805	1.1931	25.5407	23.8452
2020/01/31 15:00	10	-0.0502	-0.0475	-0.0210	0.1000	219.4561	55.4763	0.0042	-0.0005	-0.0017	0.0005	0.0180	0.0086	0.0040	-0.0021	-0.0008	-0.0230	-0.0164	0.0030	0.0003	0.0065	0.0085	0.0037	0.0045	0.0059	0.6256	0.4076	0.4670	0.0649	0.0635	0.7910	22.2561	21.4529

Table 5-8: An example of ten 30-minute time outputs of the various final meteorological parameters (including the H_s and H_{fw}) output by the datalogger for the SR calibration

TOA5	CR1000	CR1000	8082	CR1000.St	CPU:2020(	47487	Met30MIN						
TIMESTAMP	RECORD	BattVolt_A	Tref_Avg	AirTC_Avg	Ts_Avg	Tfw_Avg	AirTC_Max	AirTC_Min	RH	RH_Max	RH_Min	Hs	Hfw
TS	RN	Volts	Deg C	Deg C	C	C	Deg C	Deg C	%	%	%		
		Avg	Avg	Avg	Avg	Avg	Max	Min	Smp	Max	Min	Smp	Smp
2020/01/29 10:00	0	12.37	23.2	22.44	23.52	22.67	22.6	22.29	55.77	58.38	55.77	1.472	6.983
2020/01/29 11:00	1	12.34	21.48	21.06	22.64	20.84	21.27	20.86	68.21	68.21	54.04	1.15	8.43
2020/01/29 12:00	2	12.34	22	21.81	24.13	23.11	21.93	21.7	62.94	71.62	62.94	1.18	4.756
2020/01/29 13:00	3	12.32	23.3	23.11	25.12	24.54	23.33	22.88	64.05	64.05	63.22	0.13	-0.02
2020/01/29 14:00	4	12.32	24.03	23.71	25.76	25.3	23.78	23.63	65.19	65.19	64.5	-0.127	-0.119
2020/01/29 15:00	5	12.33	24.42	24.11	26.27	25.28	24.2	24.01	66.31	66.31	66.01	-0.203	-0.146
2020/01/29 16:00	6	12.32	24.64	24.39	26.21	25.64	24.48	24.29	67	67	66.72	-0.372	0.072
2020/01/29 17:00	7	12.31	24.78	24.54	26.47	25.94	24.6	24.47	67.59	67.59	67.29	-0.581	-0.025
2020/01/29 18:00	8	12.34	24.82	24.59	26.64	25.81	24.6	24.57	67.62	67.62	67.49	-1.663	-0.276
2020/01/29 19:00	9	12.32	24.82	24.61	26.75	25.59	24.63	24.58	67.31	67.8	67.31	-2.082	0.508

5.2.2 Field calibration

The ATI sonic was set up in the Shooter's Hill, KwaZulu-Natal grassland site at the same height as the SR thermocouples (2.0 m). Data was collected for a two-week period Plate 5-7).

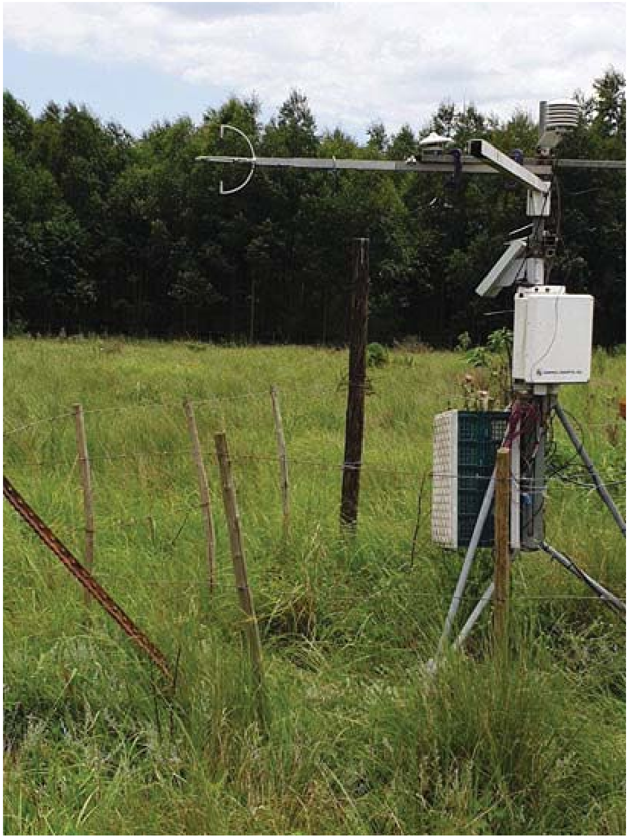


Plate 5-7: Sonic anemometer and weather station

The diurnal trends in the sensible heat flux from both the SR and ATI sonic EC systems showed very clear positive agreement, particularly on clear days (e.g. 12 to 13 February: Figure 5-42). Since the sonic transducers are sensitive to water, periods of poor data were removed from the calibration period (especially 7 to 11 February: Figure 5-42), which was characterised by frequent rain.

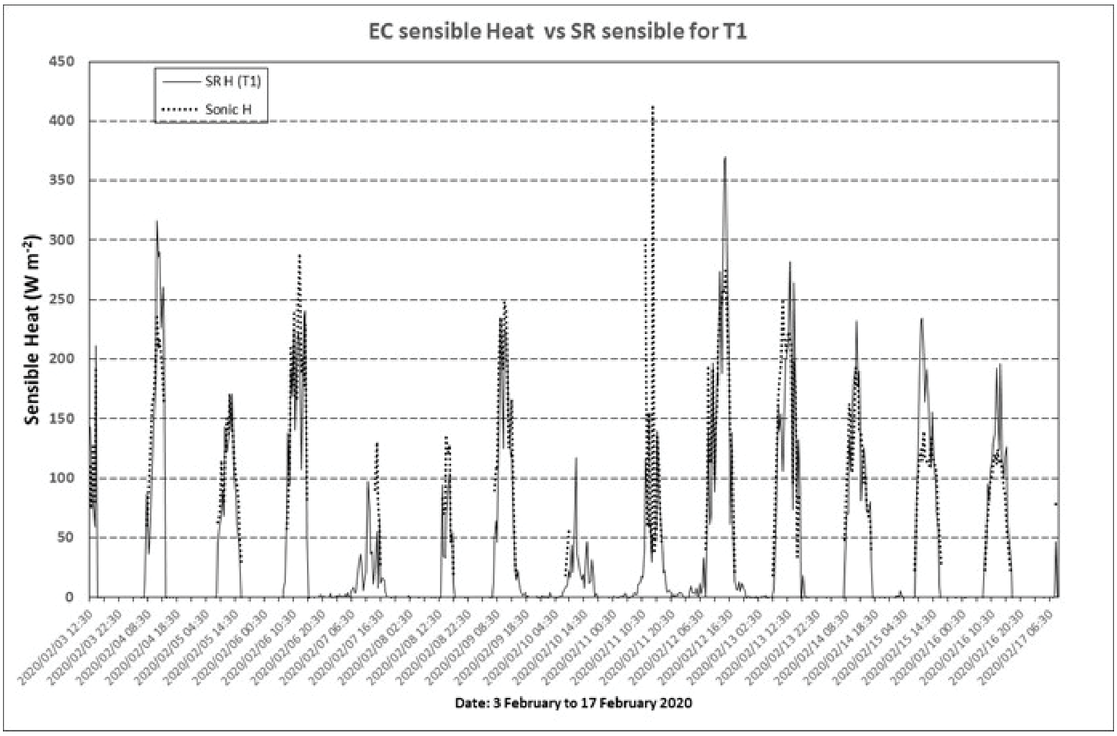


Figure 5-42: The diurnal trends in the EC sonic and SR sensible heat flux at Shooter's Hill

Linear regression of both the SR T1 and T2 sensors was performed against the 30-minute sonic sensible heat flux (Figure 5-43 and Figure 5-44) for the two-week calibration period. Both SR-derived sensible heat values showed a good linear correlation with the EC sonic $H_{s.}$ The R^2 values accounted for ~ 70% of the variation. The SR T1 (when forced through the origin) had a good 1:1 relationship (Y = 0.93), while the T2 slope indicated that the SR was over-estimating the sensible heat flux by ~ 21% (Y= 0.79). The uncalibrated data could then be adjusted using alphas of 0.93 and 0.79 for T1 and T2, respectively, using the iterative procedures developed by MJS Savage at the University of KwaZulu-Natal (Figure 5-45). Where possible, missing data was patched with an operating TC in cases where the alternate failed. For the September 2018 to February 2020 study period, approximately 25 000 lines of 30-minute sensible heat flux and energy balance data were generated. The calibration factors were applied to the daily time step spreadsheet to reduce processing time.

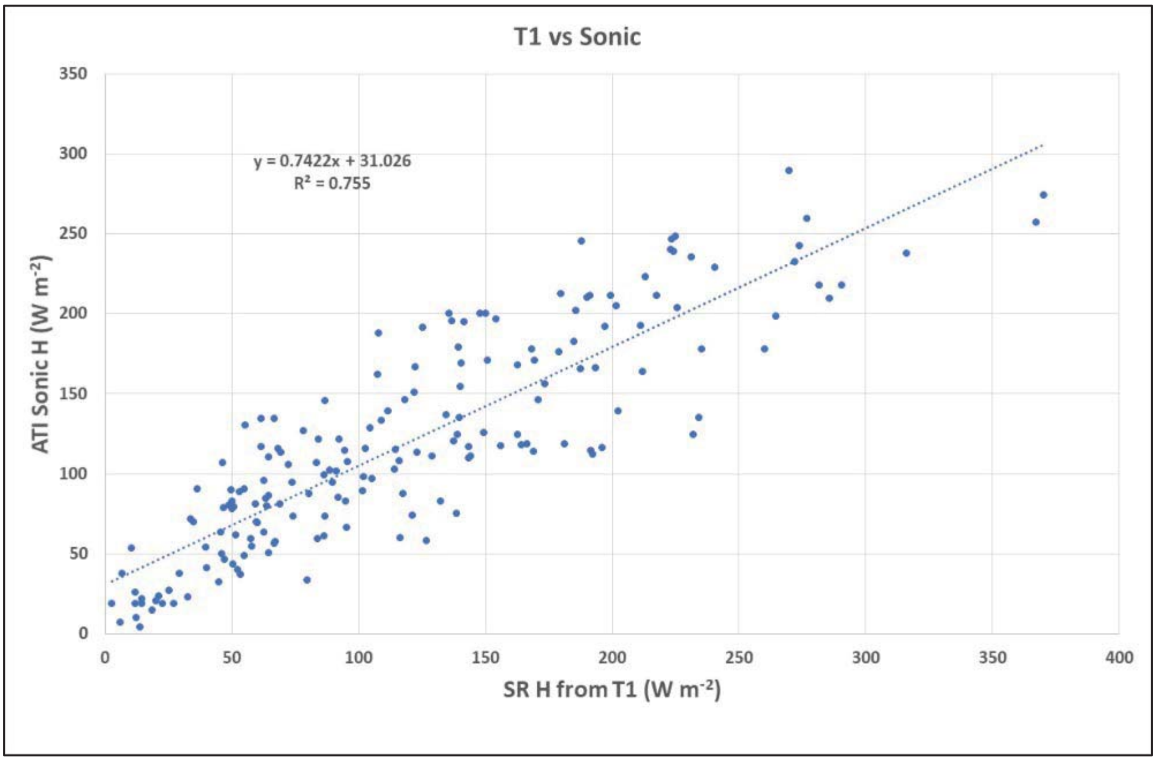


Figure 5-43: Regression of the SR T1 sensor and the sonic sensible heat flux

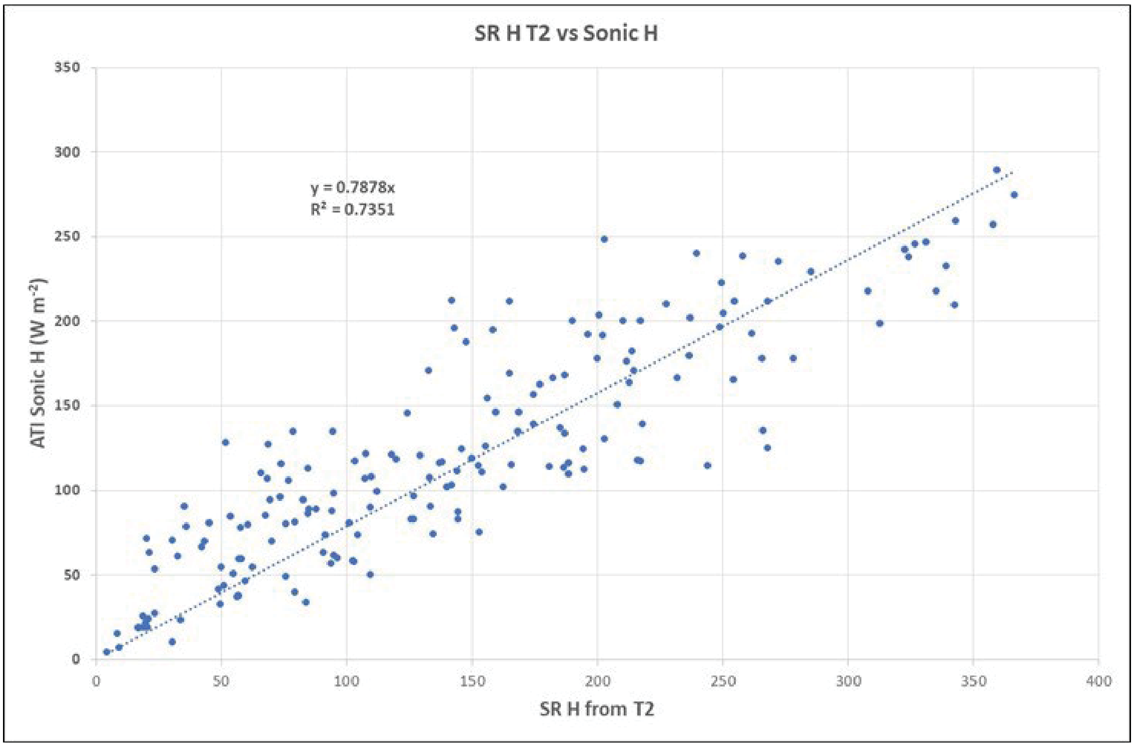


Figure 5-44: Regression of the SR T2 sensor and the sonic sensible heat flux

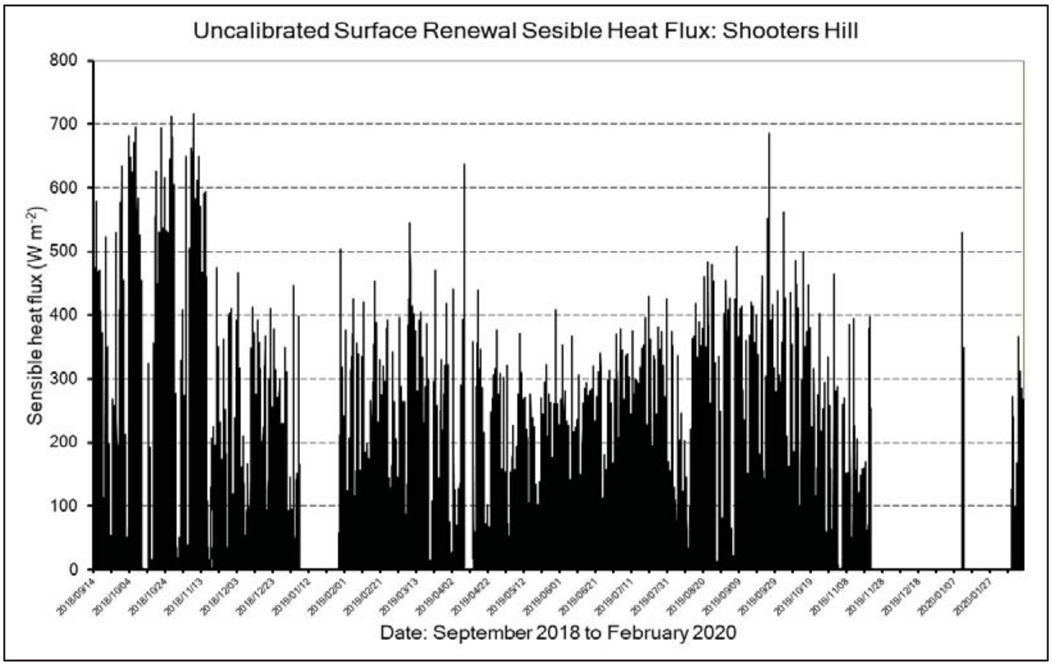


Figure 5-45: Uncalibrated surface renewal sensible heat flux at Shooter's Hill, KwaZulu-Natal

5.2.3 Energy balance results

Monitoring the energy balance at the grassland site was carried out from September 2018 to February 2020, providing an almost complete annual energy balance grassland data set for the KwaZulu-Natal baseline natural grassland (Figure 5-46 to Figure 5-49).

Maximum daily net irradiance increased, as expected, from the start of the measurement period in September, to > 800 W m^{-2} over the summer solstice on 22 December 2018, and again in December 2019 (Figure 5-46). The net irradiance at night was generally greater than -100 W m^{-2} with a few nights dropping to -200 W m^{-2}. From mid-February, the net radiation showed a smooth decline at midday (maximums reaching < 400 W m^{-2} from June onwards) as the winter sun angles declined and the day length shortened around the winter solstice on 21 June 2019. The site was mostly characterised by clear sunny days with a few rainy events (e.g. the rain event from 24 to 26 January 2019). Daily maximum net radiation was < 100 W m^{-2}.

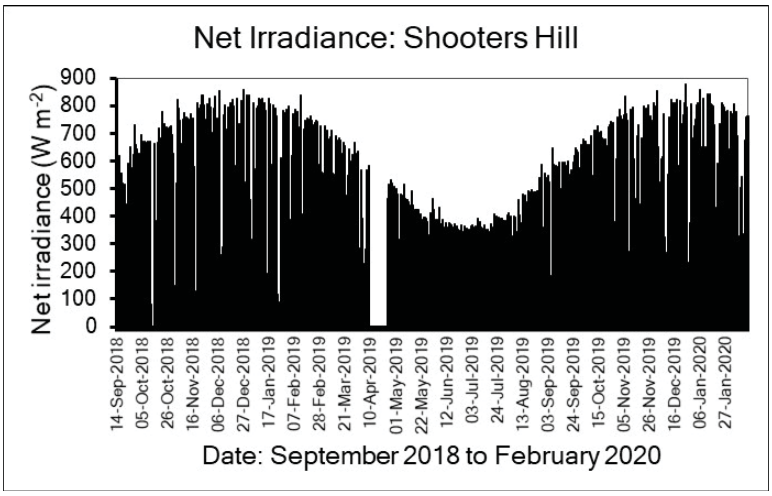


Figure 5-46: Net radiation measured every 30 minutes at the Shooter's Hill grassland site from September 2018 to February 2020

The soil heat flux at Shooter's Hill fluctuated between approximately -40 W m^{-2} at night and a maximum of 120 W m^{-2} during the day between September and November 2018 (Figure 5-47). Thereafter (mid-December), the daytime soil heat flux started to decrease, reaching maximums of only approximately 50 W m^{-2} as the growing canopy of the grassland provided more cover from the direct solar radiation. By the end of summer (February), maximum midday values dropped below 50 W m^{-2} and continued to drop until mid-winter in response to the decrease in daily energy as a result of the concomitant decrease in net radiation, which dropped from > 800 W m^{-2} in summer to < 400 W m^{-2} in winter. The soil heat flux represented approximately 12% and 7.5% of the net radiation in summer and winter, respectively.

The calibrated surface renewal-determined sensible heat flux was measured from September 2018 to February 2020 (Figure 5-48). The data presented here represent the final derived SR heat flux. The sensible heat flux over the grassland reached a peak at the start of spring (October and early November) of approximately 600 to 700 W m^{-2} during the day. From mid-December 2018 until the end of February 2019, the sensible heat flux's upper boundary was approximately 400 W m^{-2} to 500 W m^{-2}. By winter (June to August), the daily maximums had dropped to between 150 and 250 W m^{-2}.

The summer pattern measured in the 2019/20 period was very similar to the 2018/19 summer. These values are important to determine the latent heat fluxes (evaporation) using the energy balance data (Figure 5-49). The season trends in the 30-minute latent heat fluxes varied from ~200 W m^{-2} in winter to > 600 W m^{-2} in mid-summer (December) (Figure 5-49). The strong correlation between the net irradiance and its seasonal course is clearly illustrated in the cyclic nature of the seasonal trends.

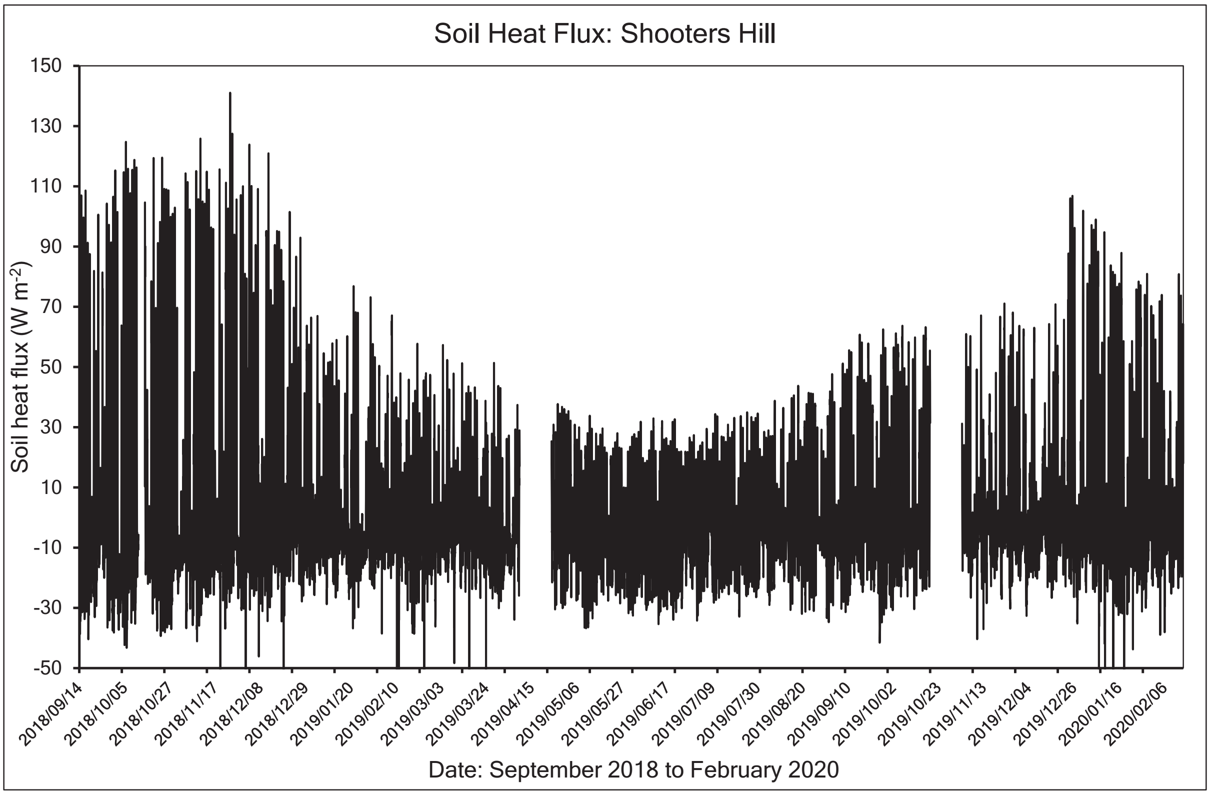


Figure 5-47: Soil heat flux measured every 30 minutes at Shooter's Hill grassland site from September 2018 to February 2020

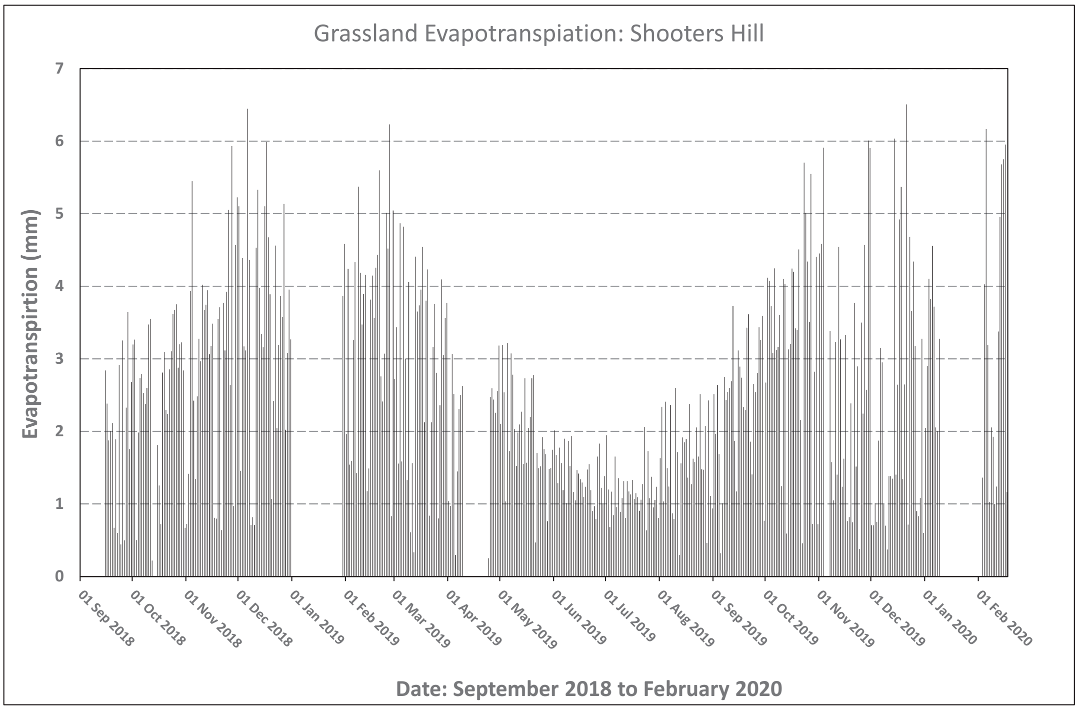


Figure 5-48: **Sensible heat flux measured every 30 minutes at Shooter's Hill grassland site from September 2018 to February 2020**

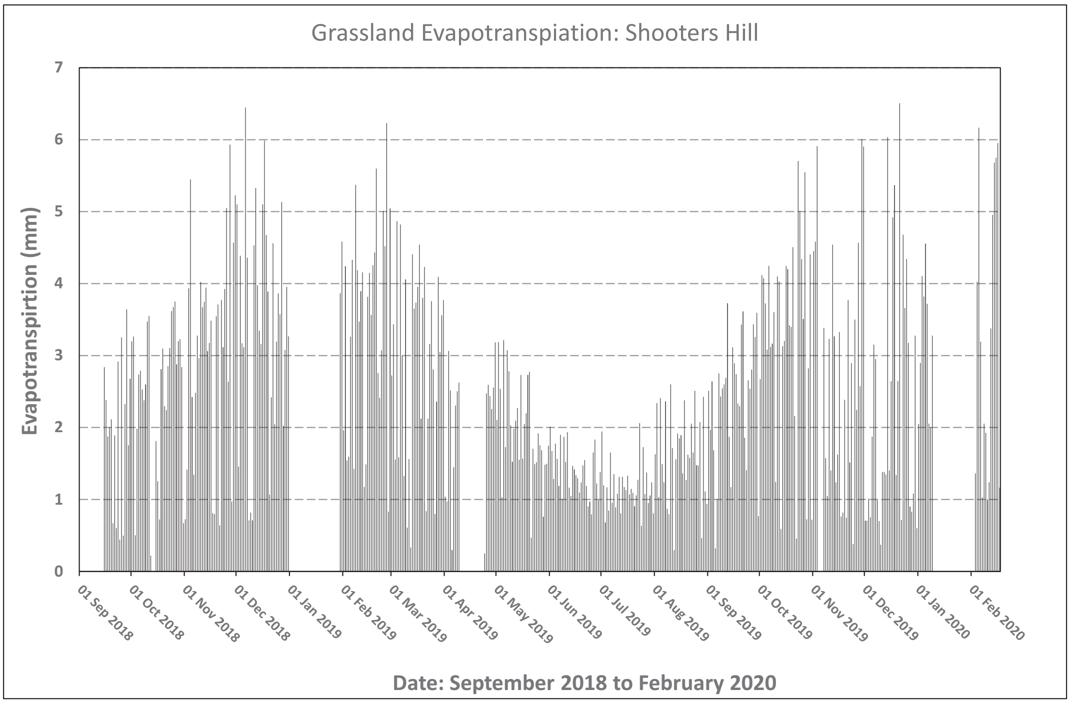


Figure 5-49: **Total evaporation measured every 30 minutes at Shooter's Hill grassland site from November 2018 to February 2020**

The average daily ET over the early period in September 2018 was 1.6 mm, while, in December, the average was 3.3 mm with a daily peak of 6.9 mm (Figure 5-50). Similar trends were recorded in 2019. There were, however, numerous days throughout the study period when the ET was limited to 0.5 to 1.0 mm. These days coincided with days of reduced net irradiance and are a result of cloudy and, in some cases, rainy conditions. By winter (June to July), the daily ET averaged only 1.4 mm day^{-1}.

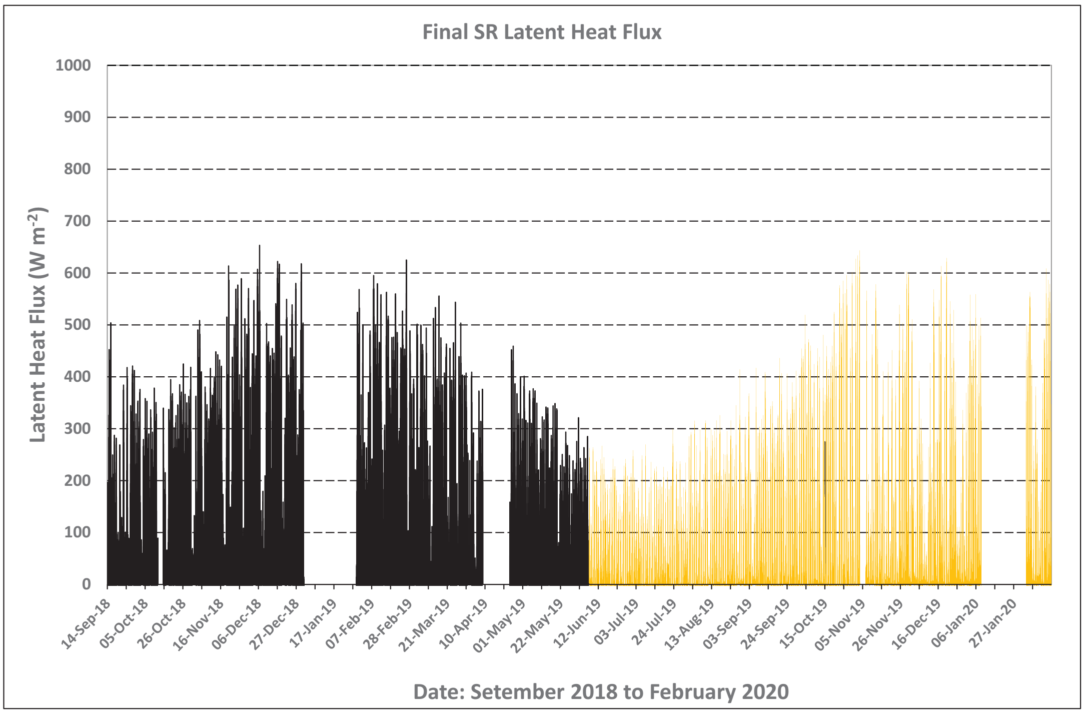


Figure 5-50: Total daily evaporation at Shooter's Hill grassland site from November 2018 to February 2020

Monthly values of the paddock grassland varied between 80 and 100 mm in summer (October to March), dropping to < 40 mm in mid-winter (July) (Figure 5-51). Total annual ET for the paddock grassland was 874 mm. Monthly ET_0 closely followed these trends, but values were consistently higher throughout the year. This resulted in K_c values of ~0.75 in summer (October to January). From February to March, the SR ET and reference ET were similar, resulting in K_c values approaching 1. K_c then dropped significantly to a minimum of 0.35 as the grassland died back in winter (July). The 874 mm annual water use for the paddock grassland showed that both the bamboo species studied in KwaZulu-Natal used less water than the grazed natural grass, while both eucalyptus and black wattle used more (see Table 5-4).

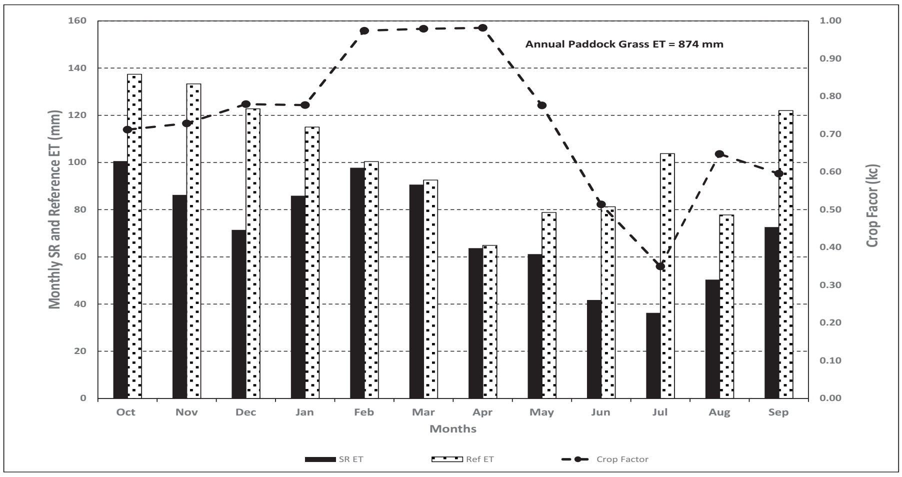


Figure 5-51: The monthly trends in the SR ET, ET_0 and K_c for the paddock grassland at Shooter's Hill for a hydrological year. Where possible, values were averaged across years.

5.3 EASTERN CAPE

5.3.1 Meteorological data

Frequent but low daily rainfall events of between 4 and 14 mm were recorded from March to April 2019 (Figure 5-52). From January to May 2020, rainfall was still low with only a few days when the rain was > 20 mm (Figure 5-52). Monthly rainfall in March, April and May (autumn) was 100, 69 and 68 mm, respectively (Figure 5-53). The annual rainfall for 2019 and 2020 was only 412 and 481 mm, respectively, approximately 200 mm less than the long-term average of 690 mm, illustrating the extent of the drought in the Eastern Cape.

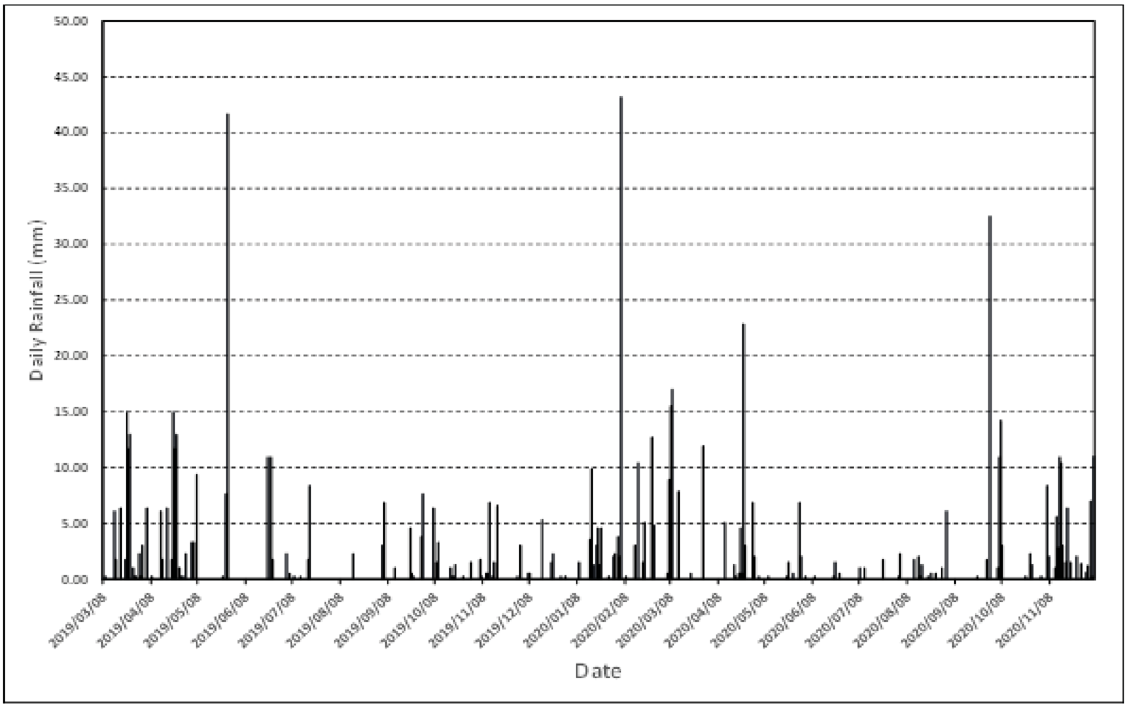


Figure 5-52: Daily rainfall at the EcoPlanet Bamboo farm from March 2019 to December 2020

The small rainfall events from March to May 2019 provided some relief in the region and resulted in a noticeable greening of the balcooa plants at EcoPlanet observed by the team during the May 2019 field trip. This was followed by very low and intermittent rainfall from June 2019 to January 2020, when only 145 mm was recorded (an average of only 18 mm month^{-1}). The late summer rains (190 mm) in February to April 2020 again provided some relief (Figure 5-52 and Figure 5-53), but were followed by an exceptionally dry period from May to September 2020, when only 45 mm fell (only 7.5 mm month^{-1}) (Figure 5-52 and Figure 5-53). Higher rainfall events from October 2020 to December 2020 (213 mm) had a positive effect on the drought-stricken bamboo plants at the EcoPlanet farm. This was illustrated by a photographic comparison of the dry condition of the plants on 9 October (before the rain), with the greening up of the same plants in November 2020 following the good rains (Plate 5-8).

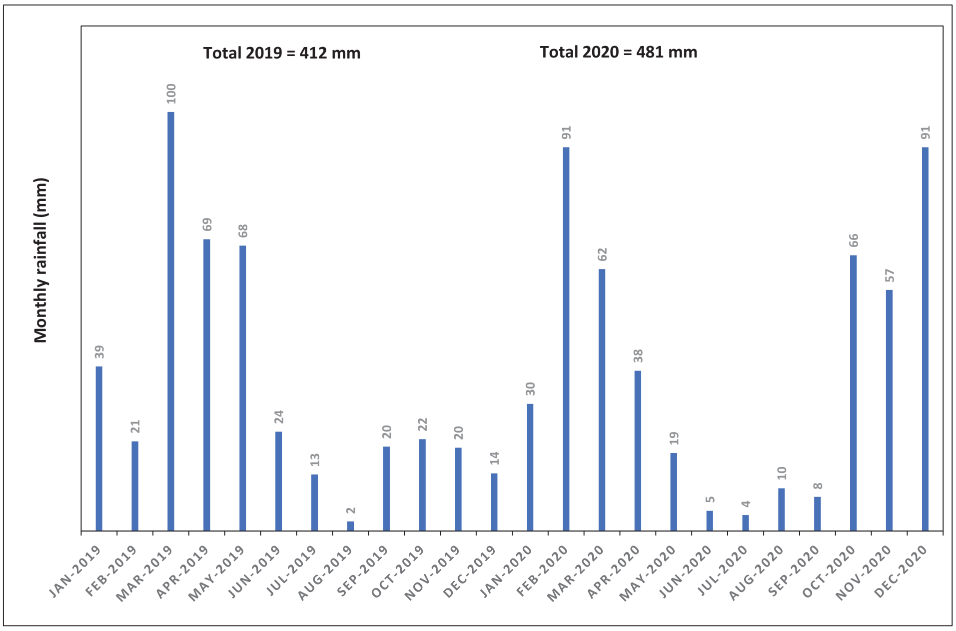


Figure 5-53: Monthly rainfall at the EcoPlanet Bamboo farm from January 2019 to December 2020

Plate 5-8: A comparison of the bamboo plants before and after good rains in October 2020

Daily climatic means of global solar radiation over 2019 and 2020 showed clear seasonal transitions. Solar radiation in summer (December) was maximal (~34 MJ), after which it decreased steadily to < 10 MJ at the time of the winter solstice (Figure 5-54). The seasonal trends showed a typical sinusoidal pattern due to the tilt of the earth's rotational axis. The data also shows the predominance of clear days in winter, while the summer period had more cloudy days, particularly from October to December 2020, when summer maximums often dropped below 8 MJ.

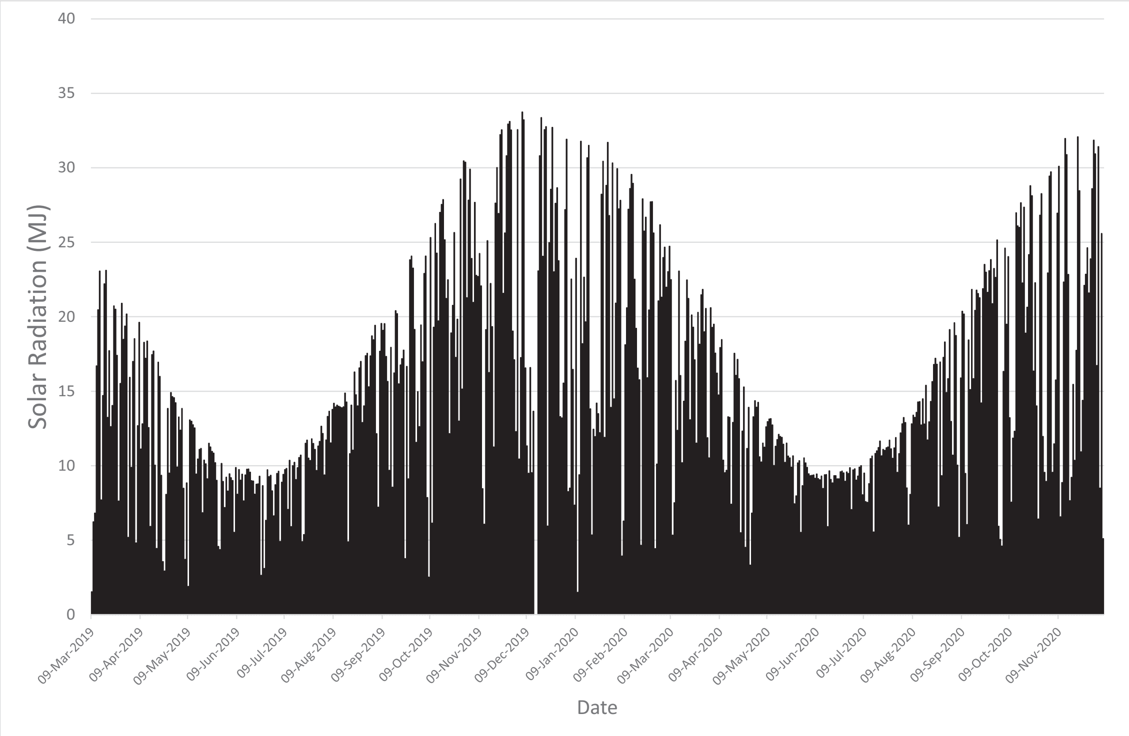


Figure 5-54: Daily trends in global solar radiation at the EcoPlanet Bamboo farm

The Eastern Cape site experienced high winds throughout the study, with average wind speeds generally above 3 m s^{-1} (Figure 5-55). Most high winds along the coastline and adjacent interior where the site is situated are caused by the passage of cold fronts. The winds are usually strongest just behind the coastal low pressure system preceding the front (Kruger et al., 2013). The sixth-order polynomial trendline fitted to the daily wind speed (Figure 5-55) was evidence of these climatic conditions producing wind, since high wind speeds were recorded in the winter months. For example, in July and August, the wind was often > 5 m s^{-1}, thereby increasing the atmospheric evaporative demand at this time. In contrast, wind gusts in summer are generally caused by thunderstorm activity. The strongest gusts from thunderstorms are usually recorded during the passages of "gust fronts" over the region, which, in turn, usually precede the first rainfall from the thunderstorm cell (Kruger et al., 2013). Since these gusts are short-lived, they are not easily seen in daily wind data. However, high winds > 5 m s^{-1} were often recorded at the study site in the summer seasons of 2019 and 2020 (Figure 5-55).

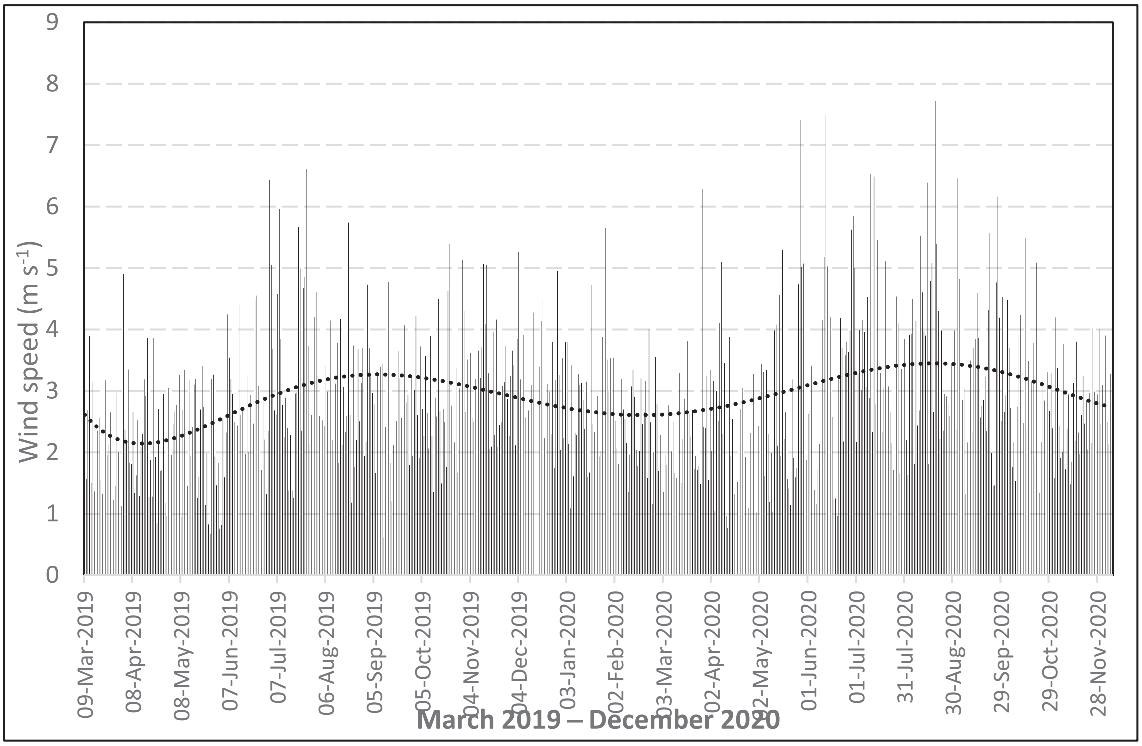


Figure 5-55: Daily trends in wind speed at Bathurst. The fitted line reprents a sixth-order polynomial

High average temperatures of between 20 and 25 °C were recorded in both summer seasons (December to February), while the winters were cooler with an average daily temperature of ~10 °C (Figure 5-56). Relative humidity was highly variable from day to day, but it was much lower on average in the winter seasons (June to August 2019 and 2020) (Figure 5-56). The combination of relatively high average winter temperatures and low relative humidity resulted in two very dry winter seasons that had a negative impact on growth and bamboo production.

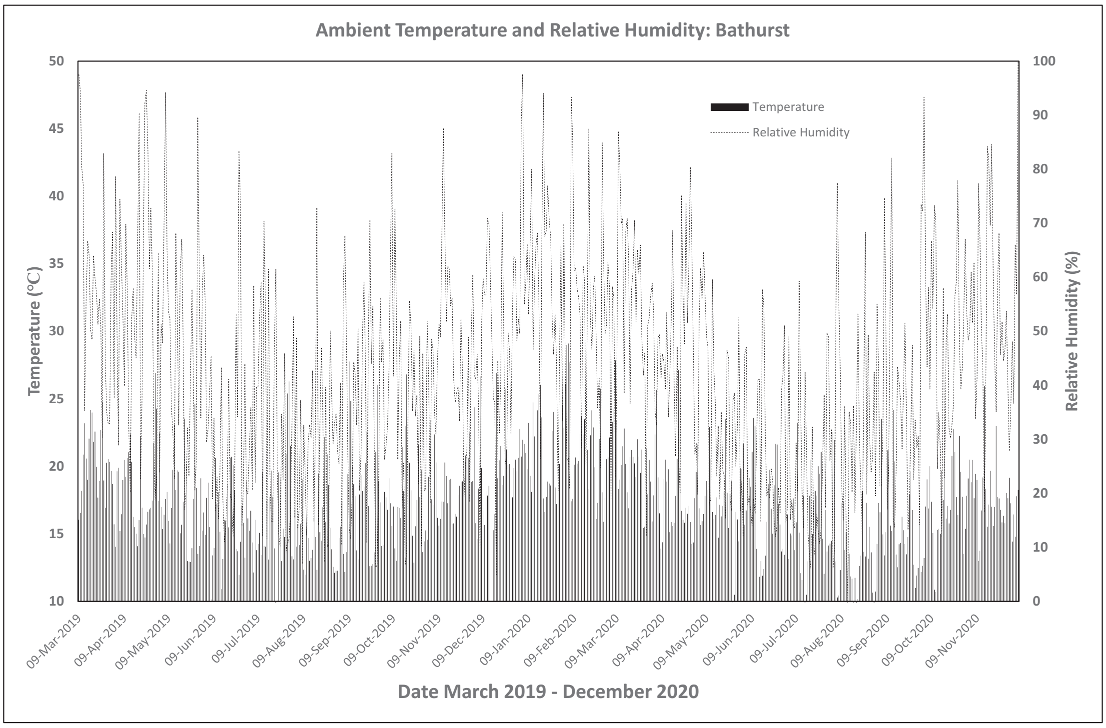


Figure 5-56: Ambient temperature and relative humidity at Bathurst

Daily ET_0 varied from highs of 6 mm in mid-summer (December and January) to < 3 mm in winter (July) (Figure 5-57). This data was used to derive the crop coefficients for the ACRU modelling.

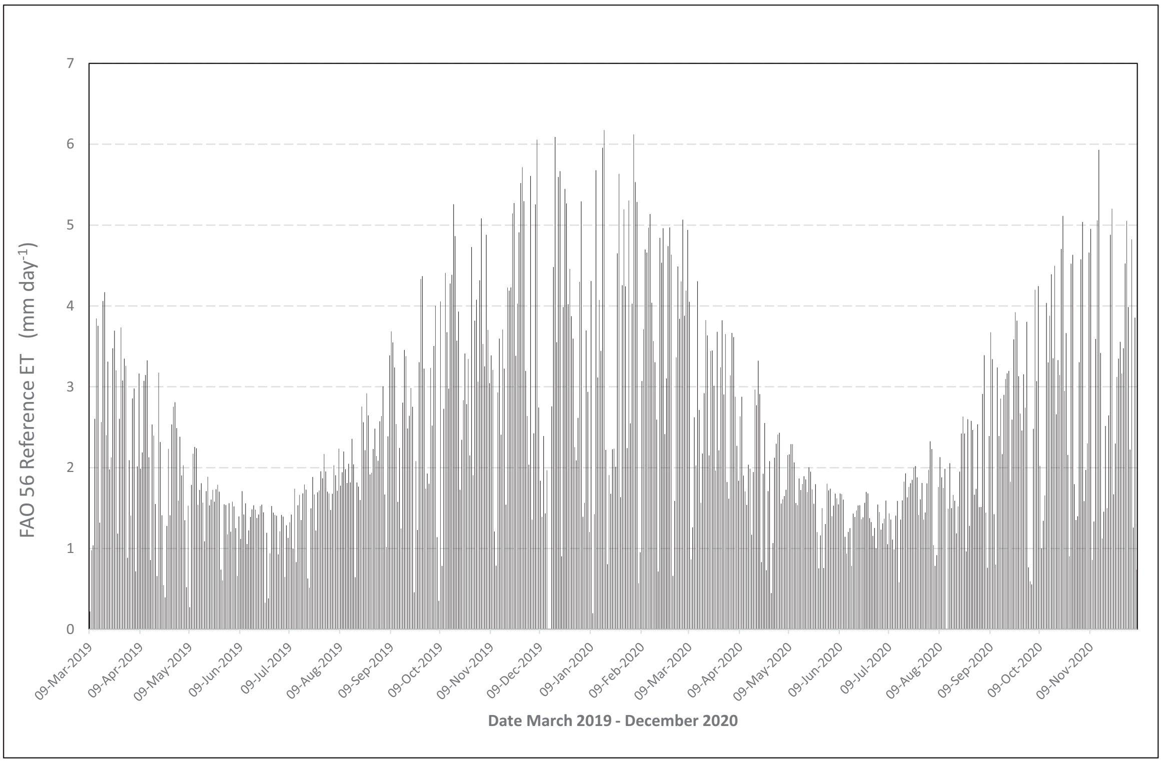


Figure 5-57: Daily reference evaporation from February to August 2019 at Bathurst

5.3.2 Soil profile water content

At the Eastern Cape site, the volumetric soil water content (VSWC) was measured with three CSI CS616 TDR probes placed at 100, 400 and 700 mm depths below the soil surface, representing a TPSWC measurement depth of 800 mm. In February and March 2019, the VSWC at all three depths declined to ~ 12% as a result of the low rainfall that occurred during that period (Figure 5-58). Both upper soil depths showed a rapid response to the arrival of the first rains in mid-March 2019, reaching maximums of 33 and 28% in the 10 and 40 mm depths, respectively. Recharge of VSWC to the 700 mm depth was only evident in late April 2019: a lag of over a month (Figure 5-58). Following this initial wetting phase, the VSWC at all three depths showed regular drying and recharge events, between 20 and 30% VSWC, resulting in the saw-tooth pattern evident in the 2019 summer to autumn seasons. With the advent of only small, infrequent rain events of < 5 mm in winter, there was a steady recession in the VSWC curve, which persisted into summer, due to the very low rainfall that was recorded from July 2019 to January 2020. By January 2020, values at all three depths dropped to below 15%. The topsoil (200 mm layer), represented by the 100 mm probe, was very dry (~ 10%), but – as expected – responded earliest to the first rains in February 2020 when the upper soil layer increased to 31%. Interestingly, at the 700 mm depth, the soil never recharged to the high values (~ 28%) seen in 2019, remaining between 13 and 16% for the rest of the study period. The surface soil reached its minimum of 8% in August 2020, when the drought was severe (Figure 5-58).

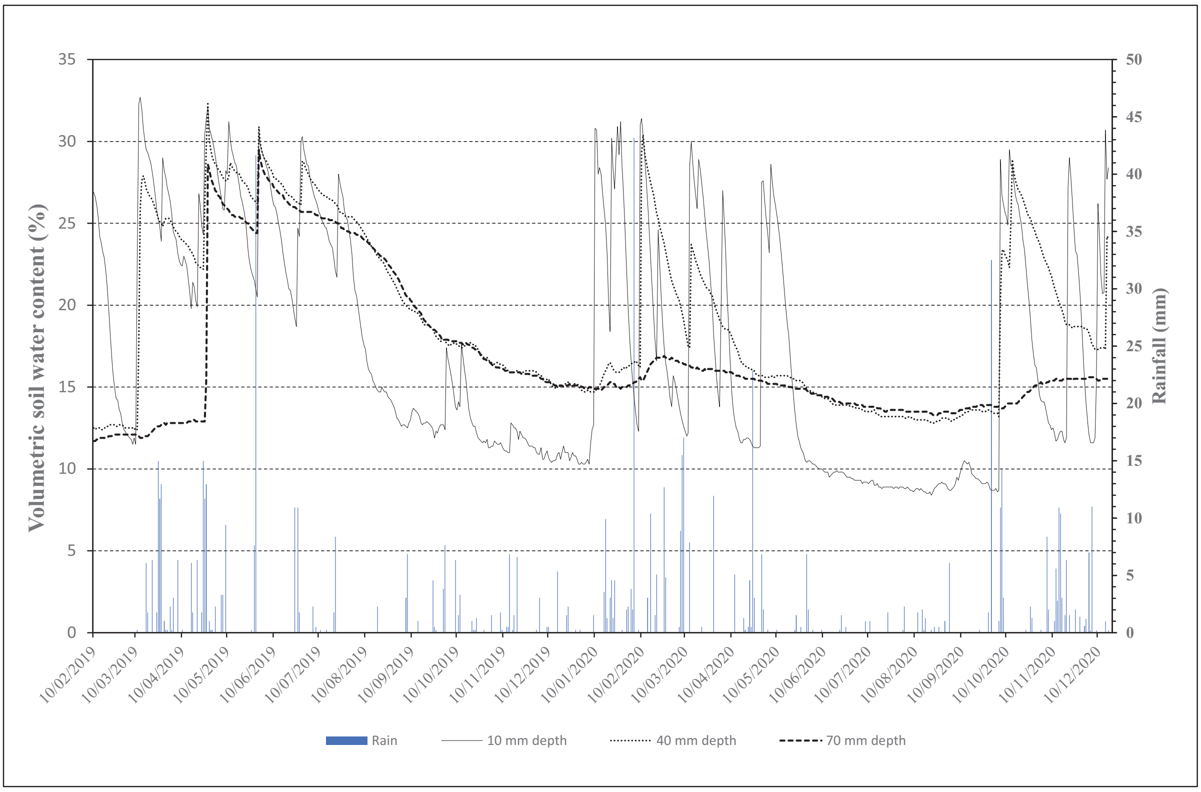


Figure 5-58: Rainfall and volumetric soil water content with respect to soil depth at the Eastern Cape site

Total soil profile water content for the 800 mm-deep soil profile between January 2019 and February 2020 varied from 76 to 185 mm (Figure 5-59). Irregular rainfall events greater than 15 mm caused large fluctuations of ~ 145 to 185 mm in TSPWC from March to June 2019. The reduction in TSPWC from 170 mm in May 2019 to less than 80 mm in November 2019 was associated with a decrease in rainfall from 68 mm in May 2019 to a low of 14 mm in December 2019 (Figure 5-59). The TSPWC at the study site showed a steady recession in both the 2019 and 2020 winter seasons when little rain fell (Figure 5-59). Assuming that the wetter conditions recorded (180 mm) corresponded with field capacity and the driest conditions recorded (75 mm) corresponded with the permanent wilting point, the maximum plant available water was ~ 105 mm in the summer.

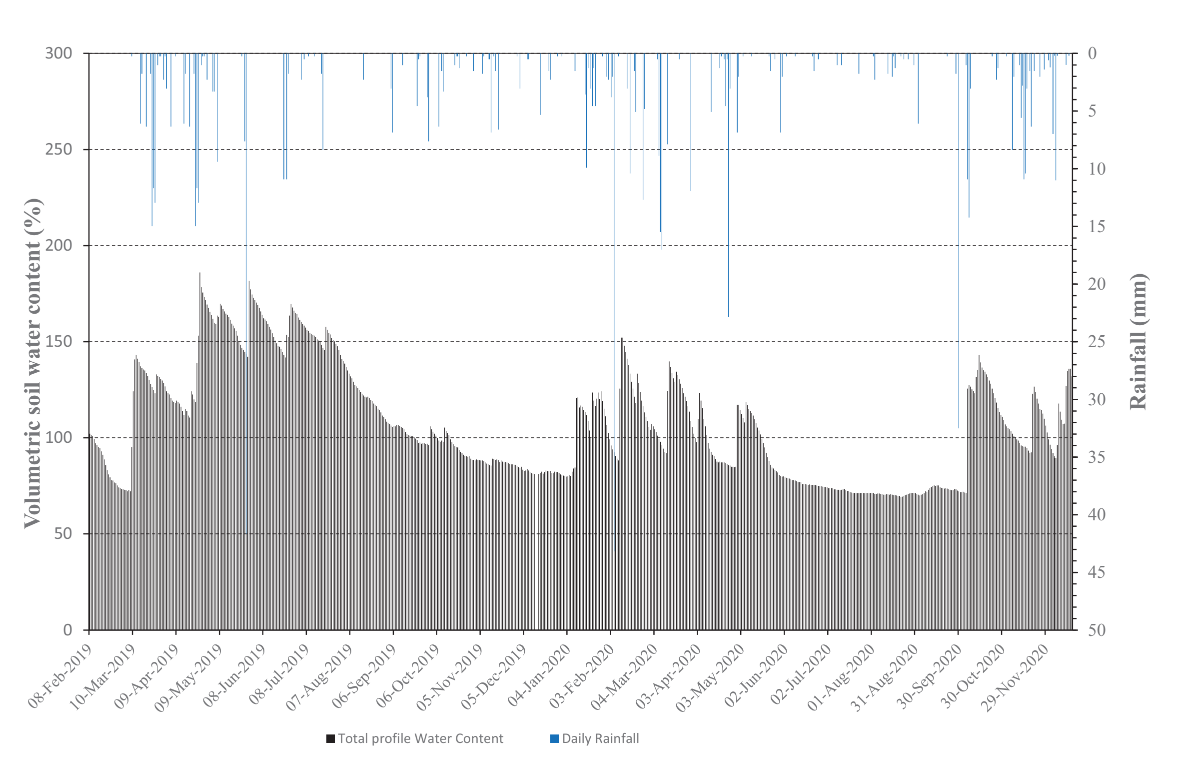


Figure 5-59: Total profile soil water content and rainfall at the Eastern Cape site

5.3.3 Balcooa growth survey in the Eastern Cape

At the Eastern Cape site, six plants were sampled, and their growth was monitored over the 18-month study period. The number of culms per clump at the start of the study varied from six to 20 with a mean of 13 culms per clump (Table 5-9). The average diameter was only 19.2 mm for these five-year-old plants, showing the poor growth performance of these plants in the Eastern Cape when compared to plants of a similar age in KwaZulu-Natal, which had diameters of up to 69 mm.

The growth of bamboo culms in the Eastern Cape was very slow with < 1% increase in diameter from a mean of 19.27 to 19.38 mm over the 18-month study period (Figure 5-60). This was significantly lower than the 26% increase in growth recorded in KwaZulu-Natal and was attributed to the severe drought.

Table 5-9: Balcooa clump size data for the Eastern Cape

Culm number	Diameter (mm)	Stem area (mm^2)	Area of hole (mm^2)	Wood area (mm^2)
Plant 1				
Stem				
1	26.50	551.77	5.8	545.97
2	19.00	283.64	5.8	277.84
3	24.00	452.57	5.8	446.77
4	19.50	298.77	5.8	292.97
5	29.00	660.79	5.8	654.99
6	12.00	113.14	5.8	107.34

Culm number	Diameter (mm)	Stem area (mm^2)	Area of hole (mm^2)	Wood area (mm^2)
7	18.00	254.57	5.8	248.77
8	22.00	380.29	5.8	374.49
9	18.00	254.57	5.8	248.77
10	10.00	78.57	5.8	72.77
11	13.00	132.79	5.8	126.99
12	12.00	113.14	5.8	107.34
13	12.00	113.14	5.8	107.34
14	7.00	38.50	5.8	32.70
Plant 2				
1	25.5	510.91	5.8	505.11
2	27.5	594.20	5.8	588.40
3	24.5	471.63	5.8	465.83
4	23	415.64	5.8	409.84
5	13.5	143.20	5.8	137.40
6	20	314.29	5.8	308.49
7	13	132.79	5.8	126.99
8	26	531.14	5.8	525.34
9	33	855.64	5.8	849.84
10	18	254.57	5.8	248.77
Plant 3				
1	27.50	594.20	5.8	588.40
2	26.50	551.77	5.8	545.97
3	28.50	638.20	5.8	632.40
4	17.50	240.63	5.8	234.83
5	22.00	380.29	5.8	374.49
6	30.50	730.91	5.8	725.11
7	18.00	254.57	5.8	248.77
8	24.50	471.63	5.8	465.83
9	10.50	86.63	5.8	80.83
10	19.00	283.64	5.8	277.84
11	17.50	240.63	5.8	234.83
12	11.00	95.07	5.8	89.27
13	13.00	132.79	5.8	126.99

Culm number	Diameter (mm)	Stem area (mm²)	Area of hole (mm²)	Wood area (mm²)
Plant 4				
1	22.50	397.77	5.8	391.97
2	17.50	240.63	5.8	234.83
3	26.50	551.77	5.8	545.97
4	22.00	380.29	5.8	374.49
5	16.50	213.91	5.8	208.11
6	16.00	201.14	5.8	195.34
7	10.00	78.57	5.8	72.77
8	11.50	103.91	5.8	98.11
9	19.50	298.77	5.8	292.97
10	22.00	380.29	5.8	374.49
11	13.00	132.79	5.8	126.99
12	22.00	380.29	5.8	374.49
13	31.00	755.07	5.8	749.27
14	8.50	56.77	5.8	50.97
Plant 5				
1	24.90	487.15	5.8	481.35
2	23.00	415.64	5.8	409.84
3	25.00	491.07	5.8	485.27
4	19.50	298.77	5.8	292.97
5	10.00	78.57	5.8	72.77
6	7.00	38.50	5.8	32.70
Plant 6				
1	27.00	572.79	5.8	566.99
2	30.50	730.91	5.8	725.11
3	15.50	188.77	5.8	182.97
4	17.00	227.07	5.8	221.27
5	19.50	298.77	5.8	292.97
6	11.50	103.91	5.8	98.11
7	8.50	56.77	5.8	50.97
8	15.00	176.79	5.8	170.99
9	7.00	38.50	5.8	32.70
10	24.00	452.57	5.8	446.77

Culm number	Diameter (mm)	Stem area (mm^2)	Area of hole (mm^2)	Wood area (mm^2)
11	9.50	70.91	5.8	65.11
12	21.50	363.20	5.8	357.40
13	25.00	491.07	5.8	485.27
14	25.50	510.91	5.8	505.11
15	26.00	531.14	5.8	525.34
16	27.00	572.79	5.8	566.99
17	13.00	132.79	5.8	126.99
18	12.50	122.77	5.8	116.97
19	17.00	227.07	5.8	221.27
20	12.50	122.77	5.8	116.97

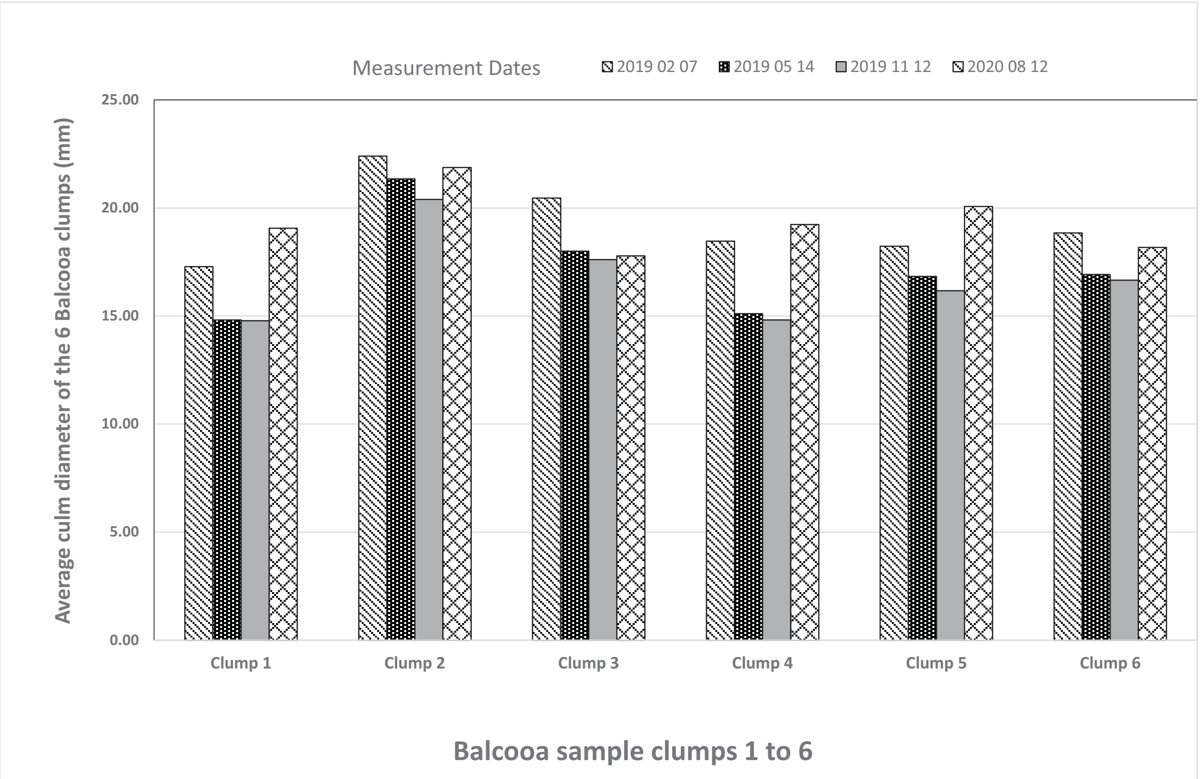


Figure 5-60: Mean growth of the Eastern Cape balcooa culms from 7 February 2019 to 12 August 2020

5.3.4 Surface renewal (Balcooa: grassland total evaporation)

The balcooa energy balance components were monitored using the 9 m mast above the 6 m-tall balcooa bamboo from February 2019 to December 2020. The daily maximum net radiation was high in summer (600–700 W m^{-2}) (Figure 5-61). From Autumn (March 2019), the net radiation declined from 500 W m^{-2} to < 300 W m^{-2} in July 2019 and 2020. The Eastern Cape site was characterised by clear days. The very dry conditions experienced in the winter season were due to the very few rain events that were recorded, when the maximum net radiation dropped below 100 W m^{-2} (e.g. 8–11 April 2019).

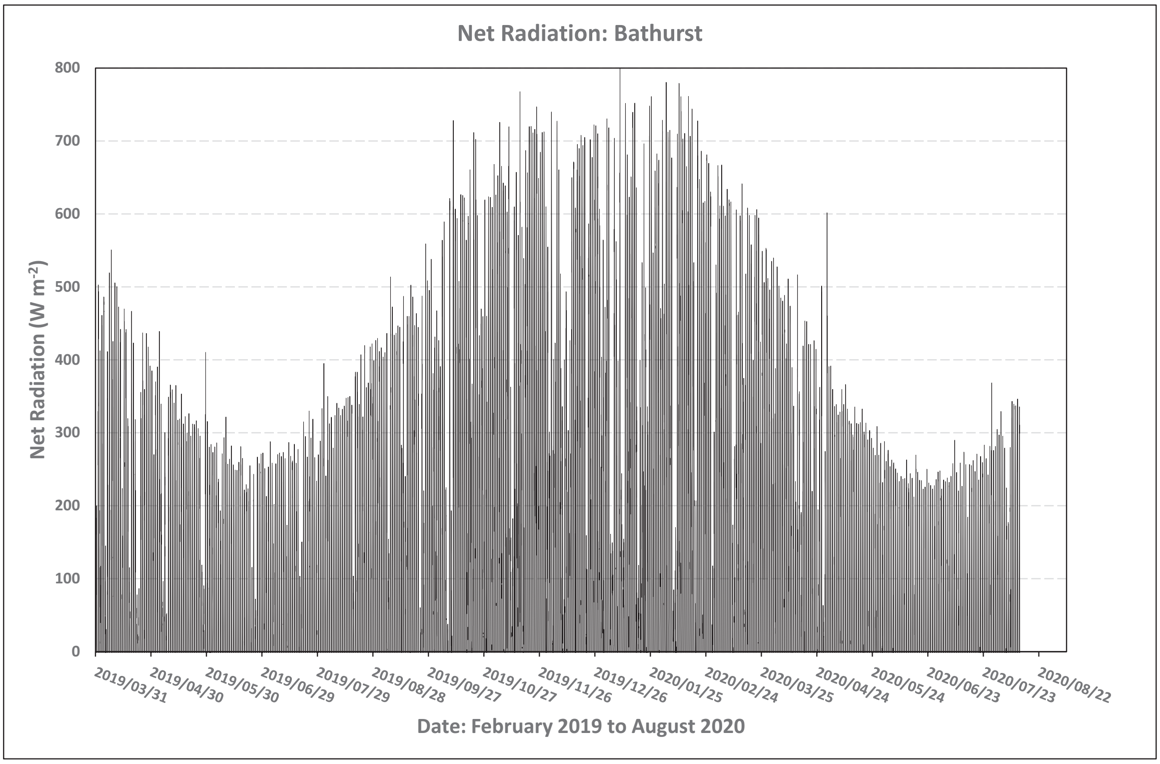


Figure 5-61: Net radiation measured every 30 minutes above the balcooa plantation at the EcoPlanet Bamboo farm from February 2019 to August 2020

At the EcoPlanet Bamboo site, the soil heat flux measured from February to December 2020 showed maximum values approaching 200 W m^{-2} during summer when the incoming global radiation was highest (Figure 5-62). Daily winter maximums were generally between 100 and 150 W m^{-2} in 2019. In 2020, the winter maximums were lower, only averaging ~ 60 W m^{-2}. This was in spite of the net radiation at the site declining steadily throughout the summer to the winter season. In summer, the soil heat flux represented about 10% of the available energy, increasing to over 15% in the winter months, as shown by the fitted sixth-order polynomial line (Figure 5-63). However, this ratio was quite variable from day to day, particularly in the winter months when the ratio was occasionally > 25%. The low grass canopy cover in between the bamboo plants in winter attributed to these results. The outcome of these relatively high percentages is a significant reduction in the available energy for partitioning into sensible and latent heat, particularly in winter when the incoming net radiation was at its lowest (Figure 5-61). The data contrasts with that at the KwaZulu-Natal grassland site where the soil heat flux was only approximately 10% of net radiation.

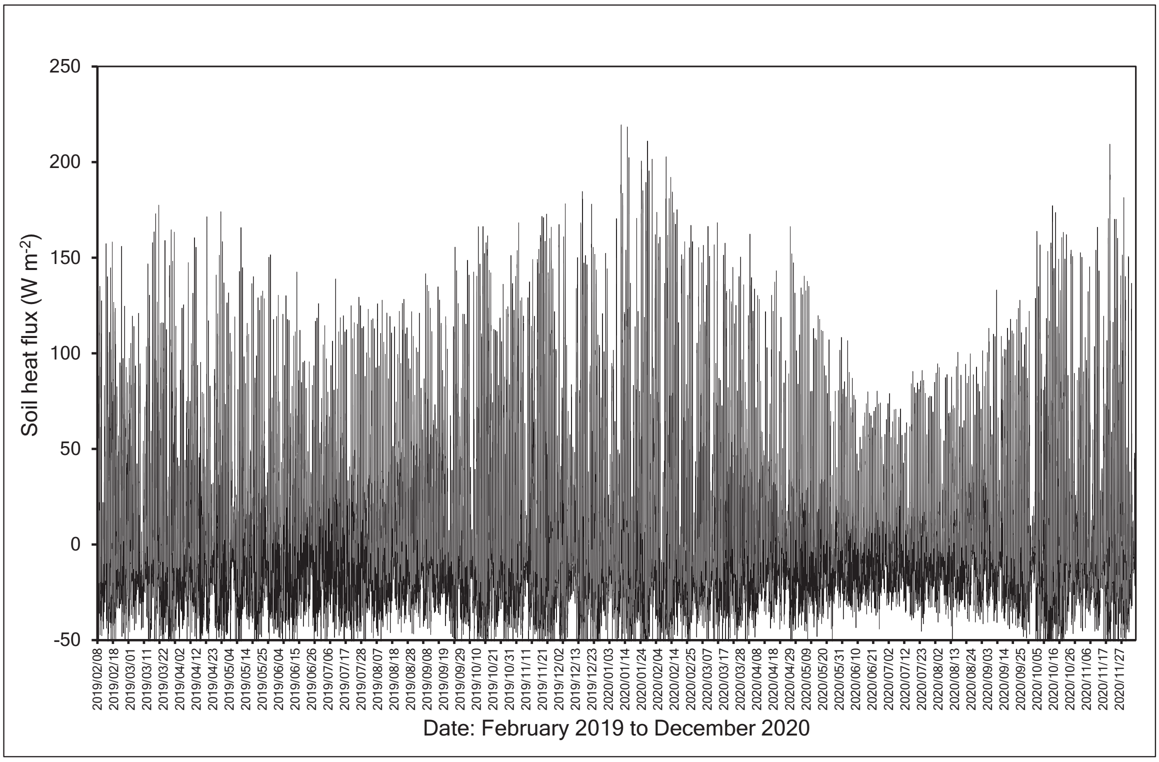


Figure 5-62: Soil heat flux from 8 February 2019 to 27 November 2020

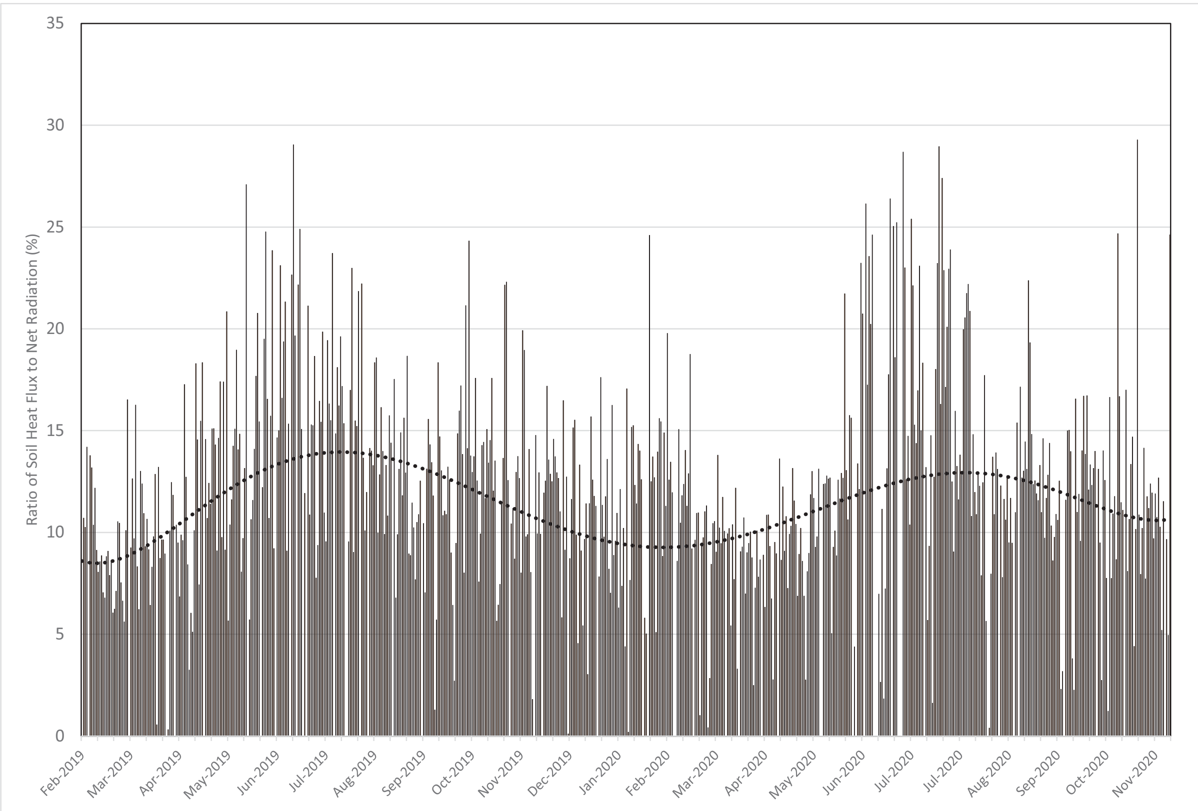


Figure 5-63: Ratio of the soil heat flux to the net radiation. The dotted line is a sixth-order polynomial fitted to the daily data between 10:00 and 16:00.

In August 2020, an Applied Technologies sonic anemometer was installed on the EcoPlanet mast at 6 m to enable calibration of the α factor for the surface renewal sensors at the site. The sonic anemometer was connected to a CR1000 data logger programmed to measure the eddy covariance sensible heat flux at 10 Hz from the vertical wind velocity and the sonic temperature and a fine wire thermocouple. Four months of 30-minute daytime data was used in the analysis. The relationship was good with an R^2 value of 0.82 (Figure 5-64). The slope of the line (α) was 0.64. This value was used to correct the raw SR-derived heat flux.

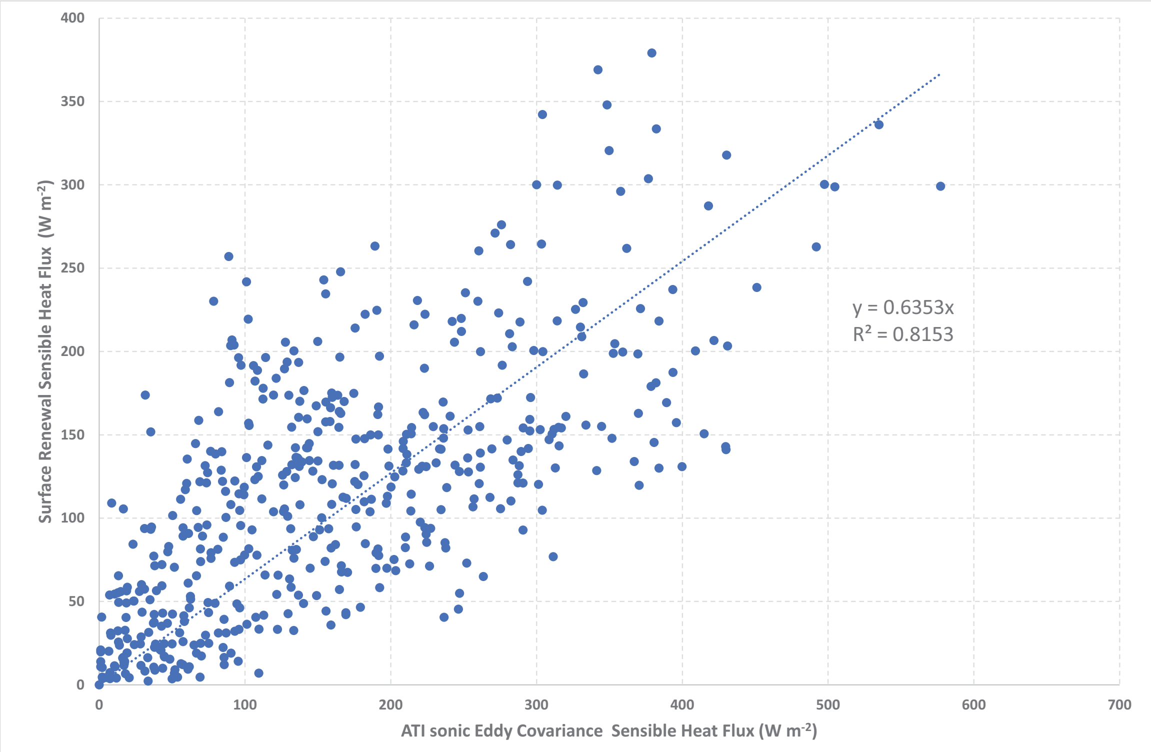


Figure 5-64: Regression of the ATI sensible heat vs the SR-derived heat flux (W m^{-2})

The sensible heat flux (Figure 5-65) at the Eastern Cape site followed similar trends to the net radiation. Maximum daily values decreased from 500 to 600 W m^{-2} in summer 2019 to below 100 W m^{-2} in winter (July 2019 and 2020). The energy balance monitoring at the Eastern Cape site was characterised by good quality data with no gaps. The three energy balance components (Rn, H and H_{fs}) were therefore used with confidence to calculate the latent heat flux (total evaporation) for the site using the shortened energy balance equation.

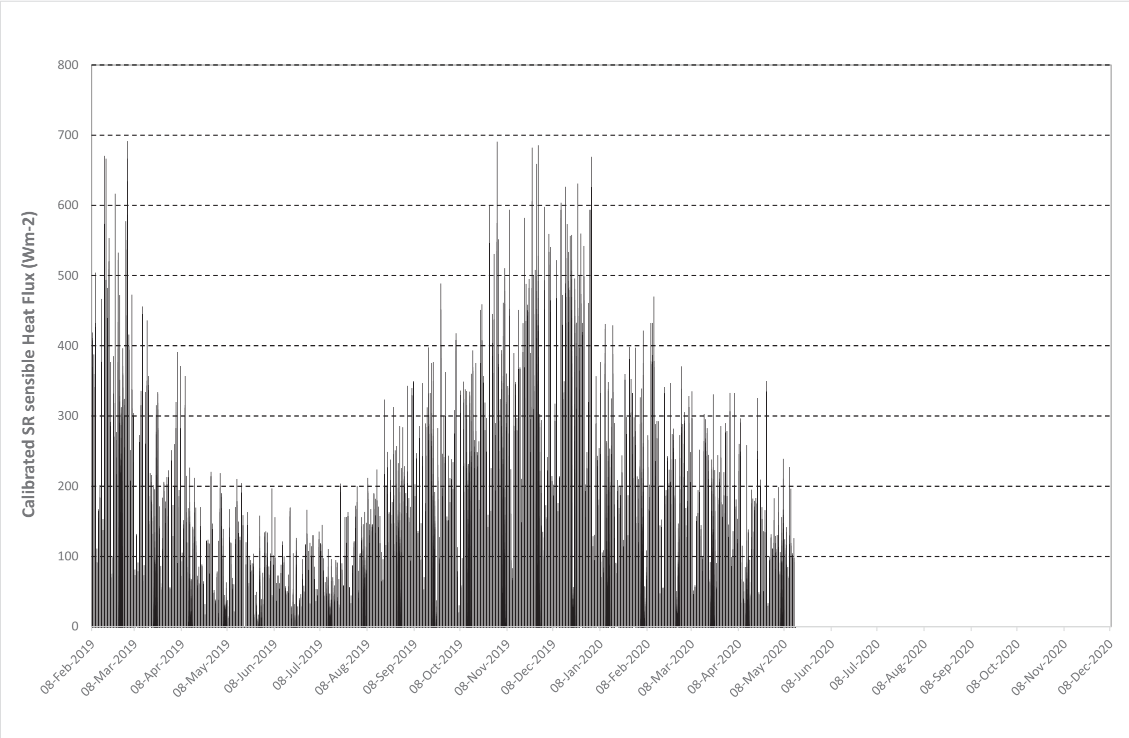


Figure 5-65: Season trends in the daily sensible heat flux at the Eastern Cape site from February 2019 to December 2020

The total evaporation from the bamboo plants and grassland at the Eastern Cape site was generally low with daily values between 2 and 4 mm in summer (February 2020) and between 1 and 2 mm in winter (Figure 5-66). Annual Et_a was only 446 and 567 mm for 2019 and 2020, respectively. This is indicative of the dry climate experienced at the Eastern Cape site during the study.

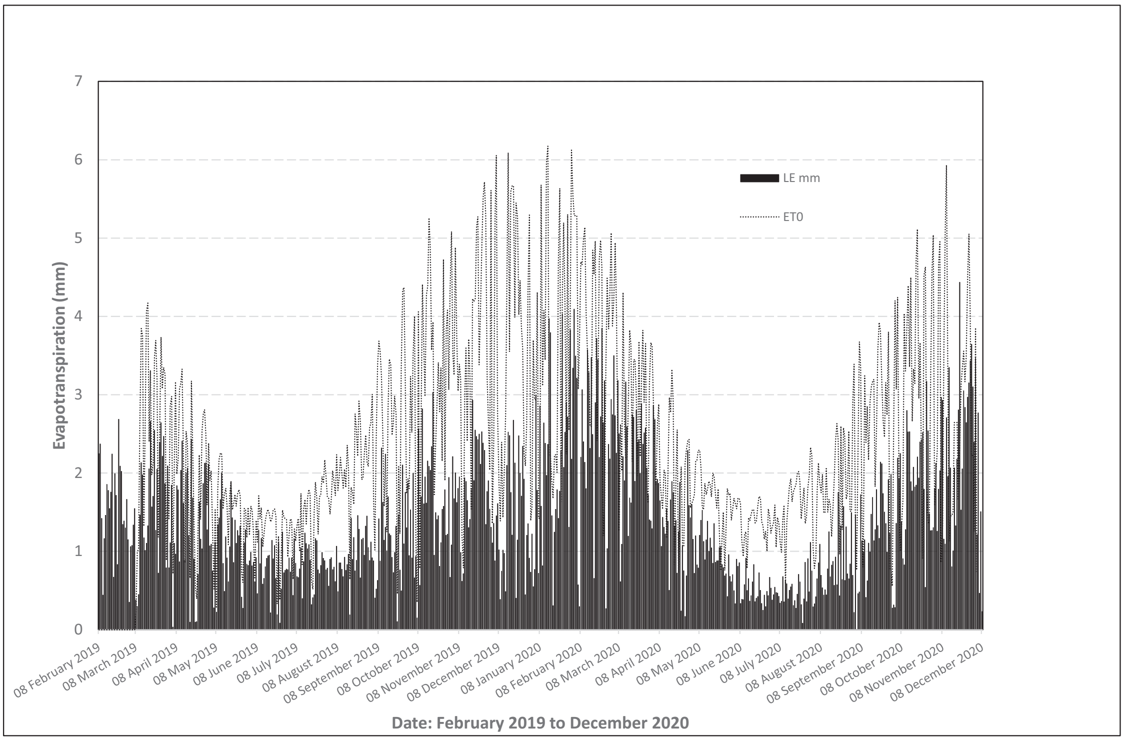


Figure 5-66: Daily total evaporation of the balcooa plantation at the Eastern Cape bamboo farm from February 2019 to December 2020

The crop coefficient depends on the specific crop type and is typically obtained empirically from experimental data such as flux towers and automatic weather stations, as was the case in this study. The rationale is to look at the ratio of observed ET_a to ET_0 (a dimensionless number) and average the sub-daily values to daily, and subsequently monthly values for hydrological modelling.

The crop coefficient therefore represents the integrated effects of changes in leaf area, plant height, rate of growth and age. In addition, the canopy resistance, management practices, soil and climate conditions all affect the K_c. Every crop will have a specific set of crop coefficients, which can be used to model crop water use for different times of the year.

Average crop factors for the Eastern Cape bamboo farm followed the seasonal cycles of the actual and reference evaporation for the site. In summer, K_c was ~ 0.77 when the crop was actively growing and transpiring, dropping to a minimum 0.45 in July when ET_0 was low and growth negligible (Figure 5-67). The December value (0.42) was an anomaly caused by the very low rainfall (14.0 mm) recorded in December 2019. For the ACRU model, the value was interpolated between November (0.78) and January (0.77) to give a more realistic model value of 0.78 for December.

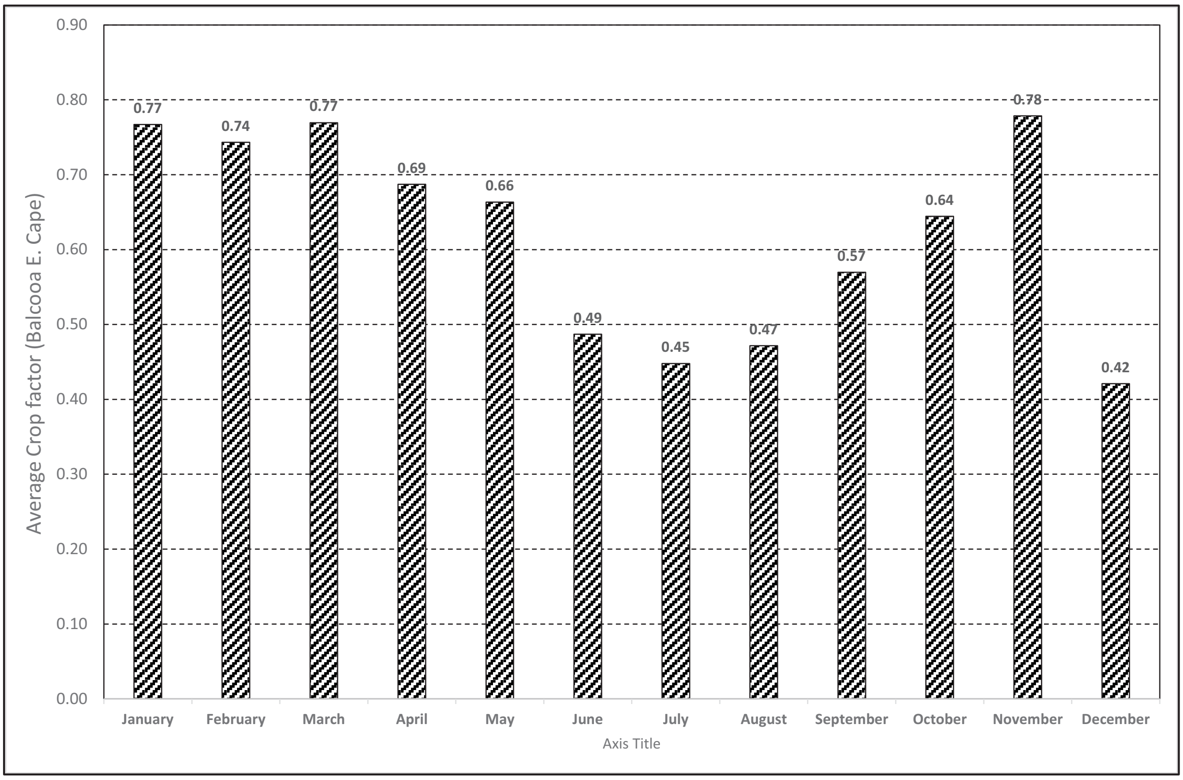


Figure 5-67: Average monthly crop factors (K_c) for balcooa in the Eastern Cape

5.3.5 SSS Bathurst

Hourly sap flow from three culms on separate clumps of bamboo with sizes close to the mean of 26.2 mm were monitored from February 2019 to December 2020. Since all the culms showed very similar trends, only a single example of a 26.7 mm culm is presented here, together with the daily rainfall (Figure 5-68). With the exception of a short period of missing data in April when the logger inexplicably stopped downloading data, nearly two years of high-quality hourly sap flow data was collected from this remote site.

The very dry February and March months in 2019 (when < 20 mm of rain was recorded) was reflected in the very low hourly sap flow rates, which remained under 100 g hour^{-1}. The bamboo plants responded to the good rain event on 8 and 9 March, when sap flow increased to a maximum of > 300 g hour^{-1} (Figure 5-68).

From April to early June 2019, the maximum rate continued at > 300 g hour^{-1} for all plants. By July, with the onset of winter, the rates dropped below ~ 150 g hour^{-1}. Interestingly, all the monitored culms responded positively to the late rain experienced on 23 June when 10.6 mm of rain fell. This data would suggest that the bamboo plants are moisture limited, even in the winter months, when solar radiation dropped to ~ 10 MJ day^{-1}. With the continued absence of any significant rain, the sap flow rate declined steadily to a minimum of only 20 g hour^{-1} by the end of December 2019. The arrival of the late rains in January 2020 resulted in an immediate response from the plants with rates increasing to > 500 g hour^{-1} by the end of January 2020. A similar pattern was found in the 2020 winter when values dropped below 20 g hour^{-1} by July 2020. Early rains in August 2020 resulted in the plants showing an immediate recovery again (Plate 5-8).

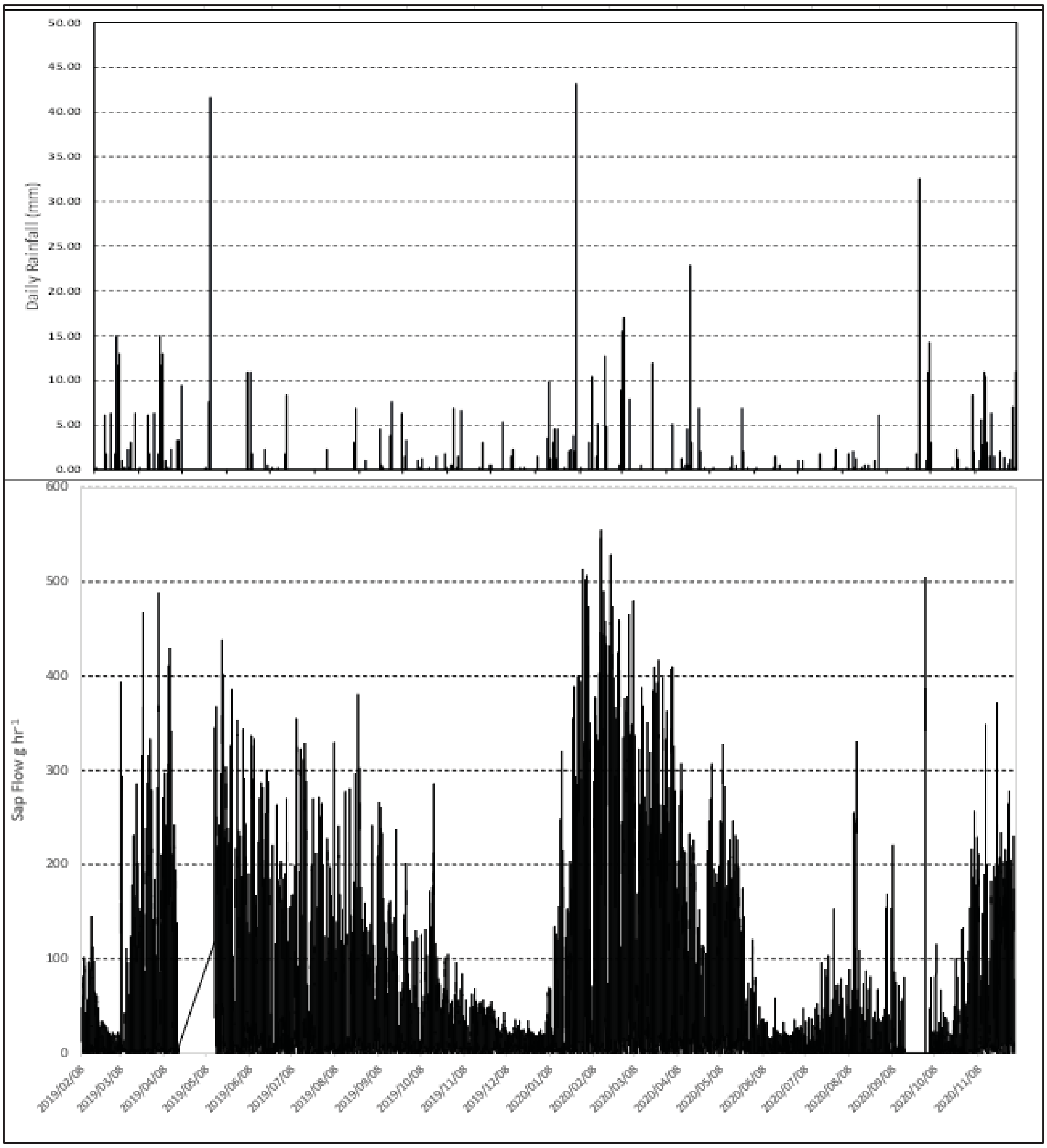


Figure 5-68: Hourly sap flow from a typical balcooa culm at the Eastern Cape bamboo farm from February 2019 to December 2020

The average daily water use of the three culms showed similar trends to the hourly data with low rates (< 0.5 ℓ day^{-1} $culm^{-1}$) in February and early March 2019 (Figure 5-69). For the rest of the season, the average rate of the three balcooa culms increased to 3.0 ℓ day^{-1} by the end of April 2019, after which it decreased to a minimum of < 0.3 ℓ day^{-1} at the beginning of January 2020. Following rain in January, the daily sap flow increased to > 4–6 ℓ day^{-1}. The 2020 winter was characterised by very low rainfall and concomitant low sap flow rates (< 2.0 ℓ day^{-1}). The plants only recovered with the spring rains in October 2020.

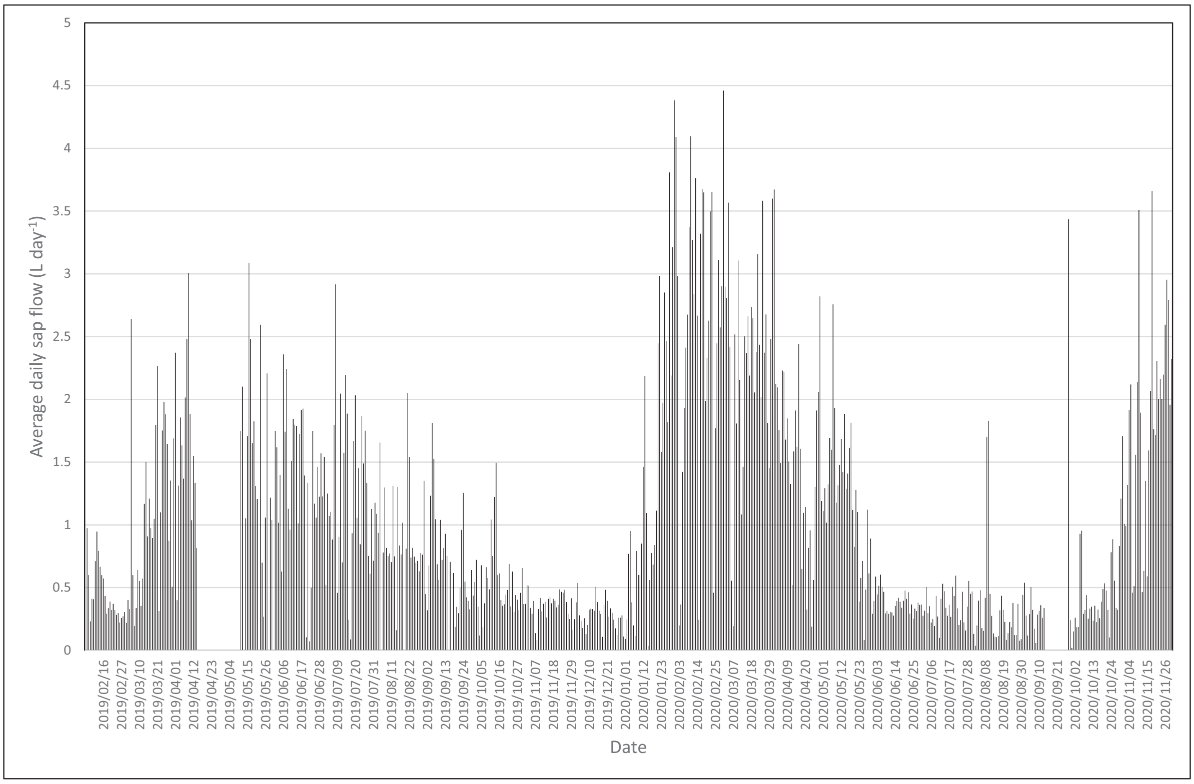


Figure 5-69: Mean daily SSS sap flow from February 2019 to November 2020 at the Eastern Cape site

Using the number of culms per clump from the six balcooa plants in the 10 x 10 m growth plot, it was possible to upscale the individual sap flow data to mm. This was based on the three frequency size classes (0–9, 10–19 and 20–29 mm) and midpoint diameter weightings for the 5, 15 and 25 mm size classes of 0.2, 0.6 and 1, respectively. Based on this, the stand transpiration was calculated for the February 2019 to November 2020 study period (Figure 5-70). Maximum rates were reached in the late summer of 2020 when daily transpiration was between 2.0 and 2.5 mm following the advent of the late summer rains after the prolonged drought period. During periods of stress, transpiration regularly dropped to below 0.5 mm (see, for example, May to October 2020). This data demonstrates the sensitivity of these shallow-rooted plants to water stress and their ability to rapidly recover once conditions become favourable again. Overall, the transpiration rates of these plants could be considered low when compared to the transpiration rates measured for the bamboo, black wattle and eucalyptus plants at the KwaZulu-Natal study site, where transpiration rates were generally much higher.

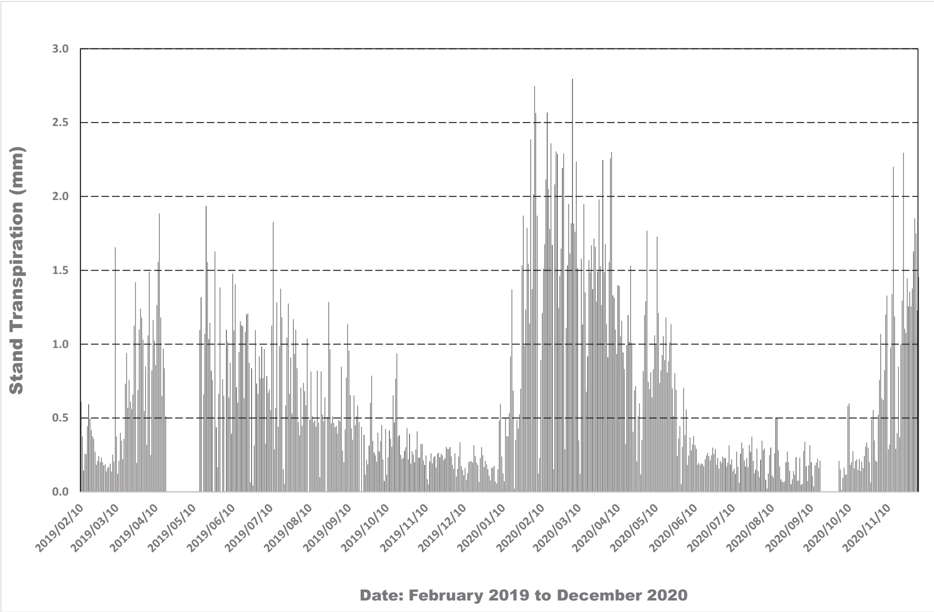


Figure 5-70: Daily bamboo stand transpiration from February 2019 to November 2020 at the Eastern Cape site

By using the total ET derived from the SR technique and the stand transpiration of the bamboo plants, it was possible to derive the contribution of the grassland ET to the total ET by subtraction (Figure 5-71). During very dry periods (e.g. October 2019 to December 2019), grass ET generally exceeded bamboo ET. This can be ascribed to the deeper rooting nature of the grass plants. When soil water was not limiting, the ET was similar for both components (e.g. January to June 2020). The total ET for the bamboo and grass was 166 and 127 mm, respectively, for the ten-month period, the grass ET being ~ 25% higher than that of the bamboo. This data shows the importance of understanding the entire system when assessing the environmental impacts of different crop systems. With good growing conditions, the bamboo system would be expected to be a "close" canopy, and the contribution of the bamboo would be much larger.

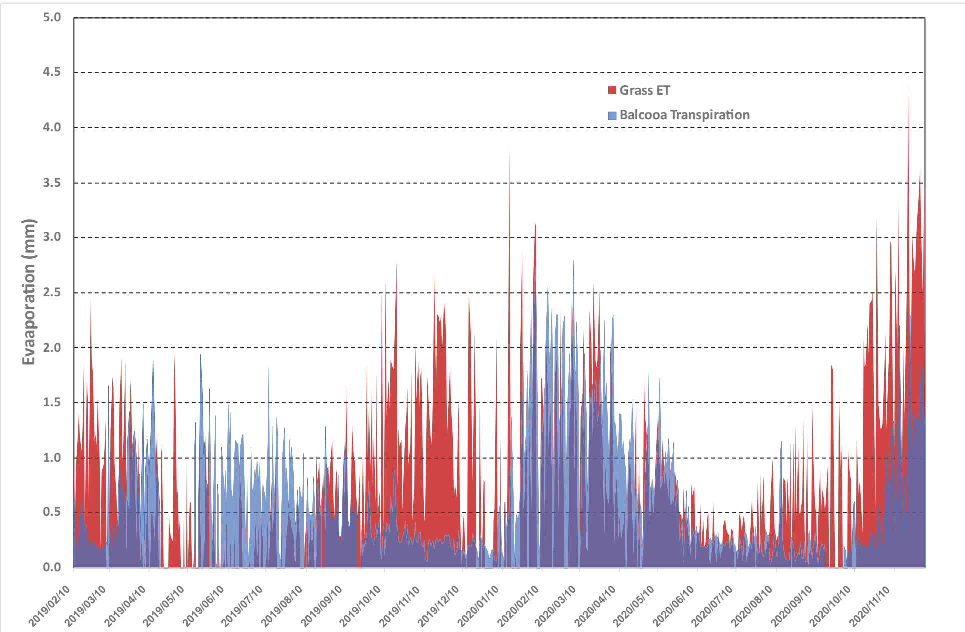


Figure 5-71: The partitioning of the bamboo's total evaporation into the grassland and bamboo ET components

CHAPTER 6: MODELLING THE STREAM FLOW REDUCTION ACTIVITY POTENTIAL OF BAMBOO

6.1 LEGISLATION AND MODEL SELECTION

The National Water Act (Act No. 36 of 1998) (NWA) enables the Minister of Human Settlements, Water and Sanitation (the former Department of Water Affairs and Forestry) to regulate land-based activities that reduce stream flow, by declaring such activities to be stream flow reduction activities. To date, only commercial afforestation has been declared a SFRA in terms of the Act. Therefore, this land use requires a licence before it can be established. Historically, in South Africa, two basic methods of stream flow reduction estimation have been developed for land-based activities that might pose a potential risk to South Africa's water resources. These are the free-standing empirical relationships in the form of the Council for Scientific and Industrial Research (CSIR)'s stream flow reduction curves (Scott & Smith, 1997), and the estimation of stream flow reduction simulated by the physical land-use sensitive ACRU rainfall runoff catchment model (Smithers & Schulze, 1995).

The empirical relationships have been used in conjunction with the Pitman monthly catchment model (HRU, 1973), while the ACRU model operates on a daily time step and can simulate any land use change (Dzvukamanja et al., 2005). The ACRU model has been shown to be sensitive to land cover, land use and land management changes, and has been used frequently in assessing these impacts on runoff (Schulze, 1995). The ACRU model has been used to assess the impact of land use change on downstream water availability for a number of different land uses, including the following:

- Commercial afforestation (Jewitt et al., 2009)
- The cultivation of potential biofuel feedstocks (e.g. sugarcane, sugarbeet, sweet sorghum, grain sorghum, soybean and canola) at the commercial farm scale (Kunz et al., 2015) and grain sorghum and soybean by small-scale farmers (Kunz et al., 2020)

More recently, ACRU has been used for the estimation of new SFR candidates such as the planned expansion of bamboo plantations.

Arguably one of the most important components of a scientific simulation model is that it should be as easy as possible to understand in light of the assumptions and mechanisms represented in the model, so that critical evaluations can be made of the predictions (Thornley, 1998). Models in the public domain are promoted and explained differently, resulting in model comparisons being more difficult than initially expected. Because numerous models developed are available for a variety of uses, a predicament exists as to which model or sub-model is best suited for the intended use. Some models are designed and developed for specific purposes, while others are more general and integrated in their applicability (Schulze, 2007). Model complexity is a major determinant as to which model is selected, as the input data available, time constraints and budget will influence model selection. The level of detail on processes, spatial disaggregation and temporal disaggregation should also be considered in models (Schulze et al., 2005).

Comparisons of simple and complex models provide insights into the model structure in order to make a suitable model selection. According to Schulze et al. (2005), models of differing complexity range from simple formulae to complex physical models. The advantage of simple models is that simple and readily obtainable inputs are required to provide estimations (Schulze et al., 2005). Simple models cannot expect to provide a detailed estimation, but they may be accurate in terms of general large-scale modelling.

Simple models should not be used to extrapolate estimates under different conditions from the ones under which these models were developed, nor for risk analysis (Schulze et al., 2005). More complex models can provide accurate estimates of hydrological components in comparison to simple models, provided that quality information is readily available, and time and money are not limited. "The development of complex models from the processes of analysis, assembly of data, model construction and validation take up costly resources in the form of skilled man hours and computer time" (Schulze et al., 2005, AT19-3).

The ACRU model was selected for this study because it could utilise the complex data collected, and the skills required to operate the model were readily available at the University of KwaZulu-Natal. In addition, the methodology of using ACRU has been accepted by the Department of Water and Sanitation and has been used on other SFRA studies, as mentioned above. The model was used with various outputs that have been widely verified against observations in many countries and conditions. ACRU was considered appropriate for meeting the objectives of the bamboo project, as the model operates as a process-based, multi-soil layer water budget, which is sensitive to land management and its changes.

6.2 THE ACRU AGRO-HYDROLOGICAL MODEL

The ACRU agro-hydrological model was chosen because it has been intensively and extensively used and verified in South Africa and utilises a sound set of databases available in the country. "The ACRU model has been developed and shown to be sensitive to land cover, land use and land management changes and has been used frequently in assessing this impact on runoff" (Schulze et al*.,* 2005. AT2-10). ACRU is a physical-conceptual model. It is physical in the sense that processes are represented explicitly with initial and boundary conditions, and conceptual in the sense that it is conceived of a system where important couplings and processes are idealised (Figure 6-1) (Schulze et al*.,* 2005, AT2-2). The ACRU model operates on a daily time step, making optimal use of available climatic information, and making the model suitable in terms of flow regimes and sediment yield, which are highly correlated with individual rainfall events (Schulze et al., 2005). This is a model of intermediate complexity.

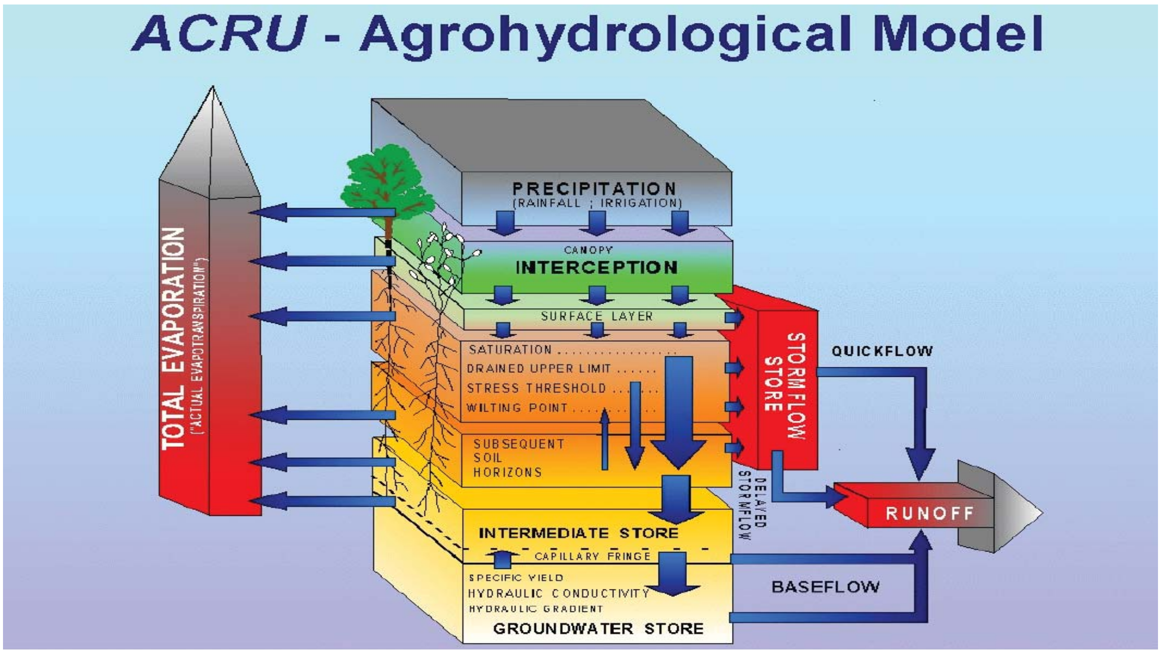


Figure 6-1: Structure of the ACRU agro-hydrological modelling system (Schulze et al*.,* 2005)

Total evaporation from a vegetated surface in ACRU consists of both soil surface evaporation (E_s) and transpiration (E_t), which is governed by rooting patterns. These can be modelled either jointly or separately. In this study, E_s and E_t were modelled separately. During periods of sustained plant stress, when the soil water content of both the upper and lower soil horizons falls below 40% of plant available water, transpiration losses are reduced in proportion to the level of plant stress. When plant available water increases to above 40% in either soil horizon, the plant stress is relieved and the evaporative losses recover to the optimum value at a rate dependent on the ambient temperature (Schulze, 2005).

6.3 ACRU MODEL PARAMETERISATION

The ACRU model considers three processes when modelling the crop water use component: evaporation from vegetated surfaces, soil water extraction by plant roots and canopy interception loss (Schulze, 2005). The key parameters that account for land cover or land use are shown in Table 6-1, of which *CAY, ROOTA* and *VEGINT* represent the minimum set that needs to be specified for each land use type. Values for these parameters were derived from field-based observations in the Eastern Cape and KwaZulu-Natal, as well as from the available literature.

Table 6-1: Key parameters (monthly values) in ACRU that account for land cover or land use (Smithers & Schulze, 1995)

Parameter	Definition
CAY	A monthly consumptive water use (or “crop”) coefficient, which reflects the ratio of water use by vegetation under conditions of freely available soil water to the evaporation from a reference surface (e.g. A-pan equivalent).
ROOTA	The fraction of plant roots that are active in extracting soil moisture from the A-horizon in a given month. This fraction is linked to root growth patterns during a year and periods of senescence brought on, for example, by a lack of soil moisture or by frost.
VEGINT	Monthly interception loss values, which can change during a plant's annual growth cycle. They estimate the magnitude of rainfall that is intercepted by the plant's canopy on a rainy day.
COIAM	Coefficient of initial abstraction that accounts for vegetation, soil surface and climate influences on storm flow generation.
PCSUCO	The fraction (expressed as a percentage) of the soil surface covered by a mulch or litter layer. This layer suppresses soil water evaporation. However, 20% of the soil water evaporation still takes place with 100% cover. Default in ACRU: 0%.
COLON	Extent of colonisation of plant roots in the B-horizon. Determines the amount of water that may be extracted by the plant from the B-horizon. Hence, this parameter reflects the extent to which the subsoil is “colonised” by roots. Total evaporation from the B-horizon is suppressed by the fraction *COLON*/100. Default in ACRU: 100%.

A sensitivity analysis undertaken by Angus (1989) for the Cedara catchment (KwaZulu-Natal Midlands) revealed that stream flow output from ACRU is highly sensitive to changes in *CAY* and slightly sensitive to changes in both *ROOTA* and *VEGINT*. Similar results were obtained by Warburton Toucher et al. (2019), based on a small (14 km^2) grassland catchment situated in the Karkloof area (KwaZulu-Natal Midlands; altitude range 800-1 200 m above sea level). Initial values for each input parameter shown in Table 6-1 were changed by ±50% to better understand the impact on stream flow generation. The results shown in Table 6-2 again highlight the importance of inputting accurate crop coefficients in ACRU. However, stream flow generation in ACRU is insensitive to changes in *COIAM*.

Table 6-2: Sensitivity of stream flow and base flow output in ACRU to increases (↑) and decreases (↓) in land cover input parameters (after Warburton Toucher et al., 2019)

ACRU output	Sensitivity to change in land cover parameter									
	CAY		ROOTA		VEGINT		COLON		PCSUCO	
	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓
Stream flow	H	H		S	S	S	I	I	M	S

Highly (10% < output change ≤ 20%)
Moderately (5% < output change ≤ 10%)
Slightly (1% < output change ≤ 5%)
Insensitive (output change ≤ 1%)

6.3.1 Crop coefficient (CAY)

The crop or water use coefficient (K_c) is used to estimate vegetation water use within the ACRU model. This coefficient is expressed as the ratio of maximum evaporation from the plant (e.g. ET_{BAM}) at a given stage of plant growth to a reference (i.e. potential) evaporation or E_{REF} (Schulze, 2005). Monthly values of K_c for each bamboo scenario were required as model inputs, and from the monthly values, daily values are computed internally in the model using Fourier Analysis (Schulze, 2005). The monthly input parameter values for the three different bamboo scenarios – balcooa (Eastern Cape), balcooa (KwaZulu-Natal) and beema (KwaZulu-Natal) – were determined by detailed plant process measurements, including both plant-based (HPV and SSS) and micrometeorological methods (SR and EC). The detailed results of the field measurements at both sub-daily and daily time scales (Chapter 5) were used to estimate monthly values of K_c. The results for the KwaZulu-Natal studies for both beema and balcooa are given in Table 6-3.

Table 6-3: Average monthly crop coefficients for the three bamboo scenarios obtained from measurements of water use in KwaZulu-Natal and the Eastern Cape

Balcooa, Eastern Cape	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_{C_REF}	0.77	0.74	0.77	0.69	0.66	0.49	0.45	0.47	0.57	0.64	0.78	0.78
E_{PAN}/E_{REF}	1.34	1.35	1.36	1.39	1.42	1.43	1.41	1.38	1.36	1.34	1.33	1.33
K_{C_PAN}	0.58	0.55	0.57	0.50	0.47	0.34	0.32	0.34	0.42	0.48	0.58	0.58

Balcooa, KwaZulu-Natal	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_{C_REF}	0.86	0.88	0.82	0.80	0.79	0.63	0.47	0.32	0.52	0.65	0.73	0.82
E_{PAN}/E_{REF}	1.34	1.35	1.36	1.39	1.42	1.43	1.41	1.38	1.36	1.34	1.33	1.33
K_{C_PAN}	0.64	0.65	0.60	0.58	0.56	0.44	0.33	0.23	0.38	0.49	0.55	0.62

Beema, KwaZulu-Natal	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_{C_REF}	0.37	0.47	0.51	0.59	0.66	0.55	0.57	0.35	0.33	0.39	0.29	0.30
E_{PAN}/E_{REF}	1.34	1.35	1.36	1.39	1.42	1.43	1.41	1.38	1.36	1.34	1.33	1.33
K_{C_PAN}	0.28	0.35	0.37	0.43	0.47	0.38	0.40	0.25	0.24	0.29	0.22	0.22

ACRU requires monthly crop coefficients (*CAY*), calculated using the A-pan as the reference evaporation. Since the K_{C_REF} values were calculated using the FAO 56 hypothetical short grass reference (i.e. E_{REF} or ET_0), the monthly values were adjusted using a pan coefficient value. Monthly pan coefficients were calculated for each quinary as E_{PAN}/E_{REF}, where E_{PAN} is the estimated monthly A-pan equivalent evaporation, and E_{REF} is ET_0. The average monthly pan coefficient values for all 5 838 quinaries in South Africa are given in Table 6-3. The pan coefficients are greater than 1 to indicate that pan evaporation is always higher than short grass evaporation. Hence, the crop coefficients for bamboo were multiplied by the inverse of the monthly pan coefficients for each quinary to determine pan adjusted crop coefficients as follows:

$$K_{C\_PAN} = K_{C\_REF} * E_{REF}/E_{PAN} = ET_{BAM}/E_{REF} * E_{REF}/E_{PAN} = ET_{BAM}/E_{PAN}$$

It is important to note that the runoff results simulated by the ACRU model were based on crop coefficients that were derived from bamboo experiments that were rainfed. Thus, the measured water use of bamboo does not represent standard conditions where irrigation is typically applied to relieve crop water stress, and thus maximise crop evapotranspiration and water use. Nevertheless, this is the accepted way of calculating actual evaporation for dryland crops where irrigation is not a factor.

6.3.2 Root fraction in A-horizon (ROOTA)

ACRU also requires the fraction of the effective rooting system in the A-horizon (*ROOTA*, i.e. the fraction of roots active in the A-horizon) to be specified month by month. During periods of plant senescence, *ROOTA* is normally set to 1.00, in which case total evaporation is computed from the soil water evaporation of the topsoil layer only.

Bamboo is a very shallow-rooted plant with rhizomes typically only growing within the first 160 mm below the soil surface (Kaushal et al., 2020). These rhizomes produce feeder roots that grow further down into the soil. Typically, the roots do not grow further than 500 mm below the soil surface. Based on the known shallow rooting habit of bamboo, *ROOTA* was set to 0.80 for each month of the year (i.e. 80% of roots in the topsoil). For the majority (4 369 of 5 838 or 74.5%) of the quinary catchments, the depth of the A-horizon (*DEPAHO* in ACRU) ranges from 0.25 to 0.30 m (Figure 6-2), which supports a *ROOTA* value of 0.80.

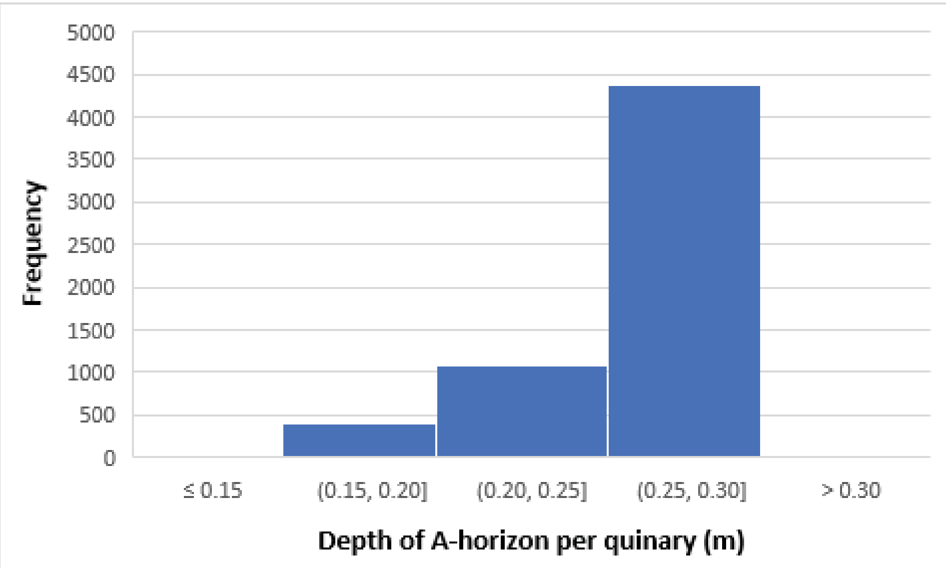


Figure 6-2: Histogram of the depth of the A-horizon per quinary (m)

6.3.3 Interception loss (VEGINT)

Canopy interception loss per rain day is set using the interception loss parameter (ACRU parameter *VEGINT*) for each month of the year and for each land use considered. These values range from 3.5 mm per rain day for mature trees grown for commercial timber production to zero for freshly ploughed land, and account for intra-annual differences in interception loss with growth stage and dormancy (Schulze, 2004). Interception loss was estimated for the 121 natural vegetation clusters from remotely sensed LAI values spanning four years using the Von Hoyningen-Huene (1981; 1983) and variable storage Gash models (Gash et al., 2005). The minimum, maximum and average monthly interception values in mm rain day^{-1} for the 121 vegetation clusters, as determined by Warburton Toucher et al. (2019), are shown in Table 6-4.

Table 6-4: Monthly interception losses derived from remotely sensed LAI values for the 121 vegetation clusters (Warburton Toucher et al., 2019)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	0.57	0.51	0.70	0.69	0.57	0.51	0.54	0.59	0.58	0.57	0.63	0.55
Maximum	2.68	2.43	2.50	2.17	1.92	1.73	1.78	1.68	1.79	1.95	2.47	2.67
Average	1.53	1.55	1.55	1.43	1.32	1.23	1.22	1.17	1.25	1.32	1.41	1.47

Since interception measurements were not within the terms of reference of this project, it was necessary to find alternative estimates of monthly *VEGINT* values. Furthermore, LAI measurements were not available at a monthly time interval for all scenarios. Thus, it was not possible to use LAI to model *VEGINT*. Since no comparable measurements of interception losses for bamboo exist in South Africa, a search of the international literature revealed an important study of interception losses for bamboo plantations in Japan (Onozawa et al., 2009). In Japan, moso bamboo (*Phyllostachys pubescens*) has rapidly invaded nearby natural or plantation forests. The only study prior to the Onozawa et al. (2009) reported that the interception ratio (interception/rainfall) of bamboo did not exceed the interception ratios of other natural and plantation forests (n = 4) in Japan. To expand this knowledge about the rainfall interception of bamboo forests, Onozawa et al. (2009) measured throughfall and stemflow at another bamboo forest site. Annual rainfall (R_f), throughfall (T_f), and stemflow (S_f) during the measurement period were 2 105, 1 556, and 322 mm, respectively. Hence, annual rainfall interception at the plot (I) was 228 mm. T_f/R_f, S_f/R_f, and I/R_f were 73.9, 15.3, 10.8%, respectively. I/R_f was less than 20% throughout the year, except in October, the month with the lowest rainfall. Onozawa et al. (2009) also summarised rainfall interception data from 19 other natural and plantation forests. Their I/R_f values did not exceed the I/R_f values of these natural and plantation forests (n = 19).

As previously mentioned, the I/Rf ratio for moso bamboo was estimated to be 10.78% (Onozawa et al., 2009). This is lower than the 14.88, 21.40 and 27.72% reported by Bulcock and Jewitt (2012) for eucalyptus, pine and wattle trees, respectively. The project modelling team therefore estimated the annual interception values as 10.78% of the quinary's long-term mean annual precipitation (MAP). Using this approach and based on MAP values for the 5 838 quinary catchments that ranged from 46 to 2 443 mm ($\bar{x}$ = 595 mm), the annual interception values ranged from 5 to 263 mm ($\bar{x}$ = 64 mm).

The annual number of rain days (NRD) per annum for each of the 5 838 quinaries was then computed and ranged from 8 to 116 ($\bar{x}$ = 53). The ratio of MAP to NRD produced values ranging from 0.45 to 3.47 mm rain day^{-1} ($\bar{x}$ = 1.20). The majority (2 024 of 5 838 quinaries or 34.7%) of the values fell between 1.00 and 1.25 mm rain day^{-1} (Figure 6-3). Only seven quinaries exhibited values above 2.68 mm rain day^{-1} (2.73; 2.73; 2.86; 2.90; 3.06; 3.14; 3.47), where 2.68 mm was the largest monthly value obtained in January for the 121 vegetation clusters (see Table 6-4).

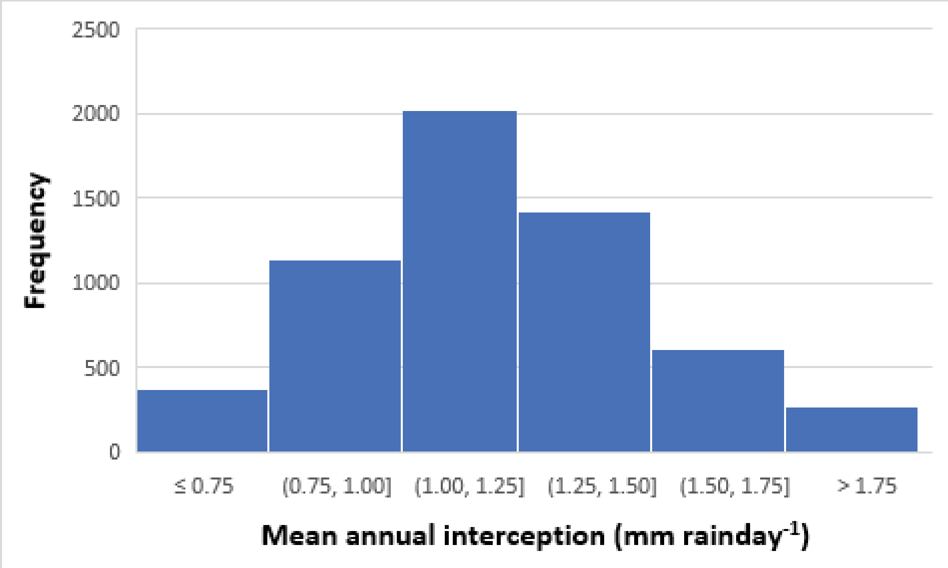


Figure 6-3: Frequency classes of mean annual interception (mm rain day^{-1}) based on a 10.78% annual interception value for bamboo

Since ACRU requires monthly interception losses, the monthly value for each quinary was set as the same annual value. Since no interception studies on bamboo have been undertaken in South Africa, this is clearly an area for future research, considering that mature bamboo plantations have high LAIs with a very thick litter layer, which would increase interception losses.

6.3.4 Coefficient of initial abstraction (COIAM)

The parameter *COAIM* in ACRU represents a coefficient given month by month to estimate the rainfall abstracted by interception, surface storage and infiltration before stormflow begins. The default value is 0.20 (20%). In urban/peri-urban areas, in arid areas and under conditions of frozen soil, it decreases to 0.05. In a month during which ploughing of lands takes place, or under afforested conditions (> 50% of catchment afforested), it increases to 0.30. For catchments with < 50% afforestation, a value of 0.20 is recommended throughout the year. For design hydrology, monthly values of 0.10 are recommended to ensure conservative design estimates. For this study, a monthly value of 0.25 was used for bamboo.

6.3.5 Root colonisation (COLON)

ACRU requires the percentage root colonisation in the B-horizon on a month-by-month basis (*COLON*). The default value is 100%, meaning that total evaporation (actual evapotranspiration) from the subsoil is not reduced by the fraction *COLON*/100. *COLON* was set to the default value of 100%, which meant that the bamboo could utilise all the soil water in the B-horizon.

6.3.6 Percentage surface cover (PCSUCO)

ACRU also requires *PCSUCO*, the percentage surface cover (mulch, litter, surface rock, etc.), which is also input month by month. Maximum evaporation (potential evapotranspiration) from the soil can be suppressed by surface covers such as mulch, litter and surface rock. It is assumed that there is a linear relationship between surface cover and evaporation from the soil. The default in ACRU is no cover, i.e. *PCSUCO* = 0.0. Suppression with 100% surface cover still allows 20% of soil water evaporation to take place. Since there are usually many dead leaves covering the soil surface in a bamboo plantation or intervening grass cover, *PCSUCO* was set to 100% for every month of the year.

6.4 HYDROLOGICAL IMPACTS OF BAMBOO EXPANSION IN SOUTH AFRICA

This section addresses the following project aim and objectives:

Aim

To quantify the evapotranspiration and stream flow reduction impacts of bamboo species on water resources in South Africa and to assess the feasibility of declaring bamboo a stream flow reduction activity.

Objectives

- Determine the evapotranspiration and stream flow reduction impact of bamboo species
- Assess the viability of declaring bamboo species a SFRA from a water resource perspective
- Extrapolate the evapotranspiration or SFR results to catchments suitable for bamboo production

6.4.1 Introduction

Section 36 of the National Water Act declares land that is used for commercial afforestation to be a stream flow reduction activity, and also makes provision for other activities (i.e. other land uses) to be so declared if this should prove justified. This would be based on such an activity being “likely to reduce the availability of water in a watercourse to the reserve, to meet international obligations, or to other water users significantly”. Thus “water use” is defined as the difference in runoff generated by the land use under consideration (e.g. bamboo plantation) and that generated under natural (i.e. pristine) conditions. This builds on the definition accepted for commercial forestry, i.e. the water used by afforestation is the reduction in stream flow compared with the stream flow that would have occurred from natural vegetation. Thus, to determine the hydrological impact of land use change to bamboo production, it is necessary to first define the baseline vegetation against which the water use comparisons are made.

6.4.2 Hydrological baseline

Until recently, the South African Department of Human Settlements, Water and Sanitation supported and accepted the use of “natural vegetation” as depicted by the veld type map of Acocks (1988) as the reasonable standard or reference land cover against which impacts of land use change were assessed (Jewitt et al., 2009). However, the Department has recently expressed an interest in adopting the 121 vegetation clusters derived by Warburton Toucher et al. (2019) as the new baseline against which all potential SFRAs should be assessed. In essence, Warburton Toucher et al. (2019) used the 2012 vegetation map produced by the South African National Biodiversity Institute (SANBI) as the new hydrological baseline. This map identifies 435 vegetation types, which were simplified into 121 hydrologically relevant vegetation groupings (clusters). For each vegetation cluster, updated ACRU model parameters were provided, with the recommendation that they be considered as the new hydrological baseline against which assessments are made, thus replacing those derived from the 72 Acocks veld types.

6.4.3 Methodology

The approach followed was similar to that used in previous ACRU SFRA studies (e.g. Kunz et al., 2015; 2020), and is as follows:

- The revised quinary sub-catchment database, together with the ACRU agrohydrological model (Schulze, 2005), was used to simulate the runoff response from a land cover of natural vegetation.
- The updated monthly rainfall adjustment factors developed by Kunz et al. (2020) were used in this study. These monthly adjustments were applied to the observed daily rainfall record obtained from the rainfall driver station to improve the representativeness of rainfall at the quinary scale.

- Solar radiation was estimated from temperature using the technique described by Chapman (2004), and Schulze and Chapman (2007).
- Daily estimates of reference evaporation for each quinary were estimated from observed temperature using the Penman-Monteith (FAO 56) method, assuming a default wind speed of 2.0 m s^{-1}.
- This study used the monthly pan coefficients developed by Kunz et al. (2015). They were derived from a comparison of FAO 56-based reference evaporation (estimated from monthly temperature), with A-pan equivalent evaporation (estimated using a modified PENPAN equation).
- These monthly adjustment factors were applied to the Penman-Monteith reference evaporation estimates to ensure that ACRU was driven by A-pan equivalent evaporation and not reference crop evaporation.
- For the baseline, ACRU input parameters derived by Warburton Toucher et al. (2019) for each of the 121 vegetation clusters (see Section 6.4.2) were used to represent natural vegetation.
- For bamboo, the parameter values given in Section 6.3 were used in this study.
- The ACRU model was used to simulate mean monthly and annual runoff response for baseline conditions (MAR_{BASE}), i.e. the runoff produced from a land cover of natural vegetation, and each of the bamboo scenarios (MAR_{CROP}), assuming a 100% change in land cover.
- The model was run at the national scale for all 5 838 quinaries, regardless of whether bamboo could be successfully grown in the quinary. The main reason for running the model for all quinaries was to avoid the scenario where, if a land suitability map for a particular bamboo species is developed or updated, additional model runs may be required for quinaries not previously highlighted as being suitable for bamboo production.
- Significant improvements were made to the model to optimise runs at the national scale, thus reducing computational expense. Each national run took approximately 23 minutes on a Core i9 PC and generated 8.5 GB of compressed model output and statistics.

6.5 RESULTS AND DISCUSSION

6.4.1 Hydrological baseline

The new baseline with 121 vegetation clusters produces more runoff along the east coast of South Africa, relative to that generated from the 72 Acocks veld types. The increase in stream flow corresponds to quinaries where the crop coefficients for the vegetation clusters are lower than those for the Acocks veld types. In contrast, less runoff is produced for the interior region of the country, due mainly to larger K_C values (especially in the winter months) and higher vegetation interception losses. Within each of the vegetation clusters, there are several vegetation types that do not senesce during winter, which explains the higher winter crop coefficients. Kunz et al. (2020) reported that less mean annual runoff (MAR) was produced in 66.6% of all quinaries, with the majority (56.1%) of differences ranging from 0 to 10 mm, followed by 8.1% of all quinaries exhibiting a lower MAR of 10 to 20 mm.

Figure 6-4 represents the MAR_{BASE} (ACRU output variable *SIMSQ*) produced from a land cover of natural vegetation as defined by the 121 vegetation clusters. The map highlights the low runoff response from the western parts of the country due to the low and erratic rainfall experienced in this region.

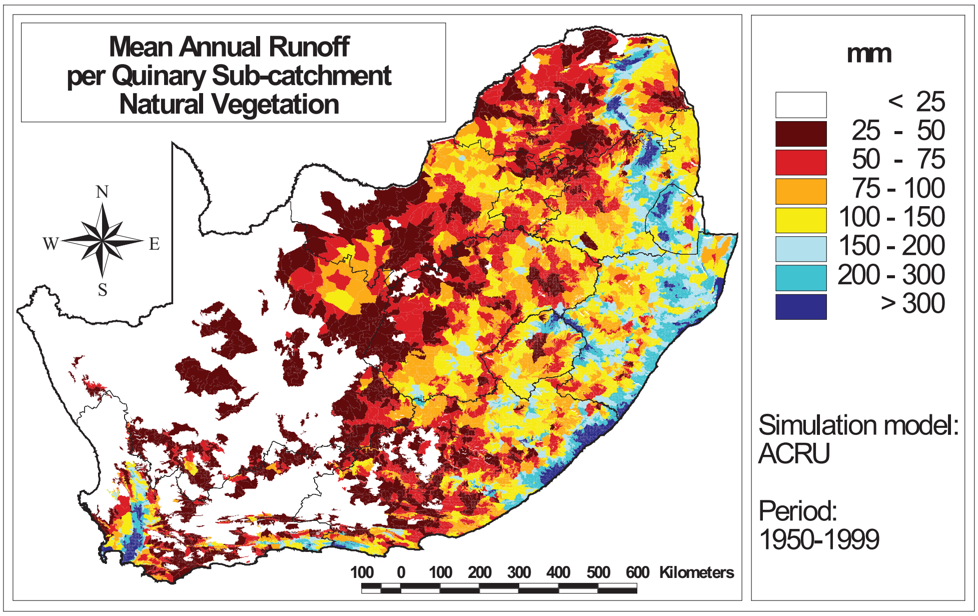


Figure 6-4: Simulated mean annual runoff from a land cover of natural vegetation as defined by the 121 vegetation clusters

6.5.2 Crop water use

The vegetation layer affects hydrological responses through canopy and litter interception, the infiltration of rainfall into the soil and via evapotranspiration loss. ACRU was also run to simulate mean annual runoff from a land cover of bamboo (MAR_{CROP}) for three scenarios: balcooa (Eastern Cape), balcooa (KwaZulu-Natal) and beema (KwaZulu-Natal). For example, the MAR_{CROP} produced from a land cover of bamboo (balcooa, Eastern Cape) is shown in Figure 6-5. When compared to the previous figure, it is somewhat difficult to visualise changes in MAR across the quinary subcatchments, except for the higher MAR produced along the KwaZulu-Natal coastline for a land cover of bamboo. For this reason, it is more appropriate to consider differences in runoff, which are typically expressed in absolute (mm) and relative (%) terms.

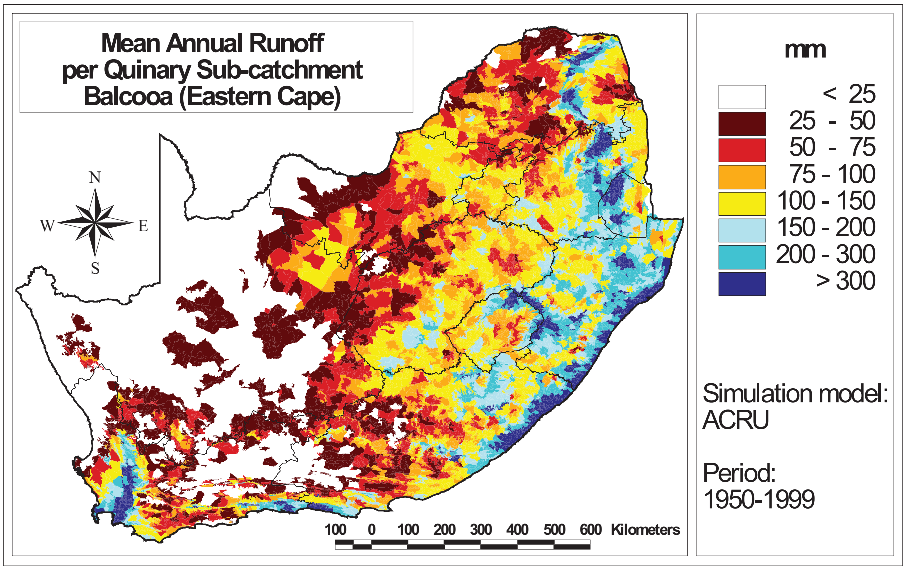
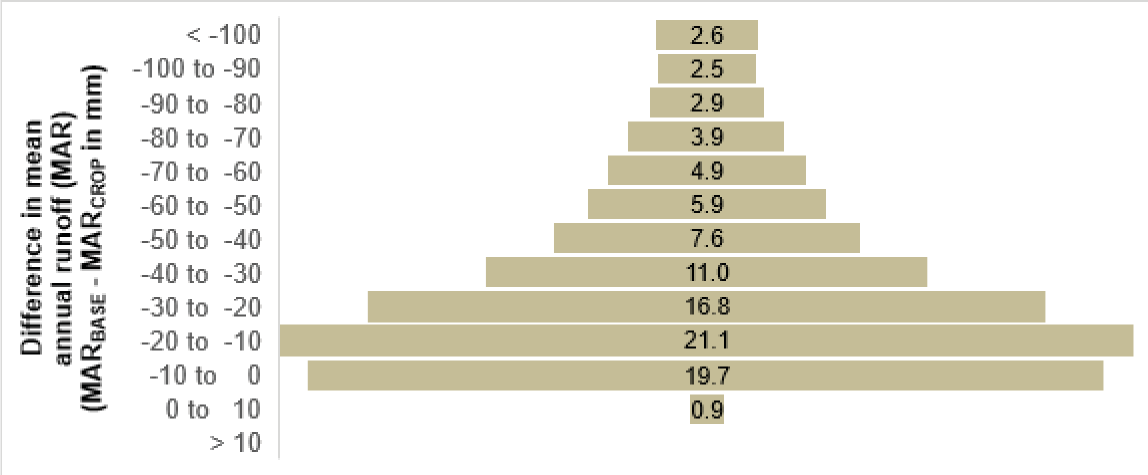
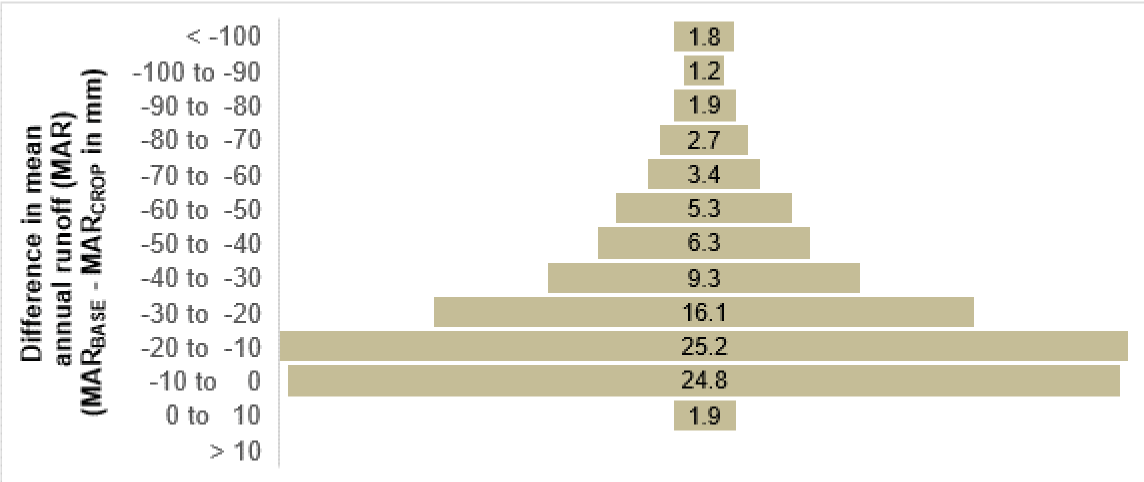


Figure 6-5: Simulated mean annual runoff from a land cover of bamboo (scenario: balcooa, Eastern Cape) for each quinary subcatchment

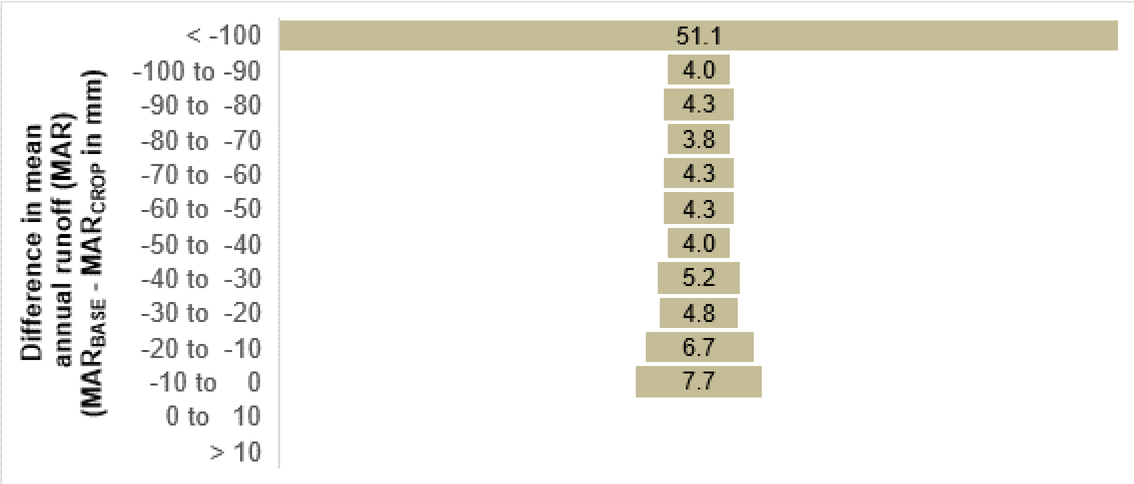
Crop water use is defined as the reduction in mean annual runoff that may result from a land-use change from the baseline (base) to bamboo (crop). The reduction in simulated MAR (i.e. MARBASE less MARCROP) can be expressed in absolute terms (mm). Figure 6-6 shows that the difference in runoff mostly ranges from -100 (or less) to 0 mm. Hence, for the majority of the quinary subcatchments, this reduction is negative, indicating that more runoff is produced from a land cover of bamboo than for natural vegetation (i.e. MARCROP > MARBASE). Hence, none of the three bamboo scenarios are likely to have a negative effect on downstream water availability.



Balcooa (Eastern Cape)



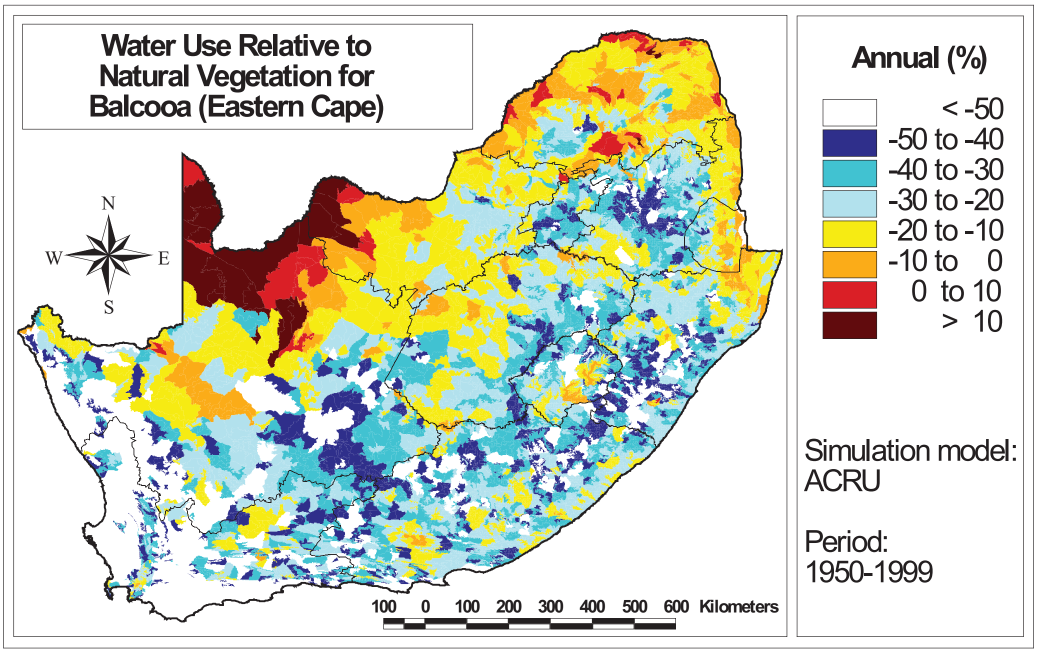
Balcooa (KwaZulu-Natal)



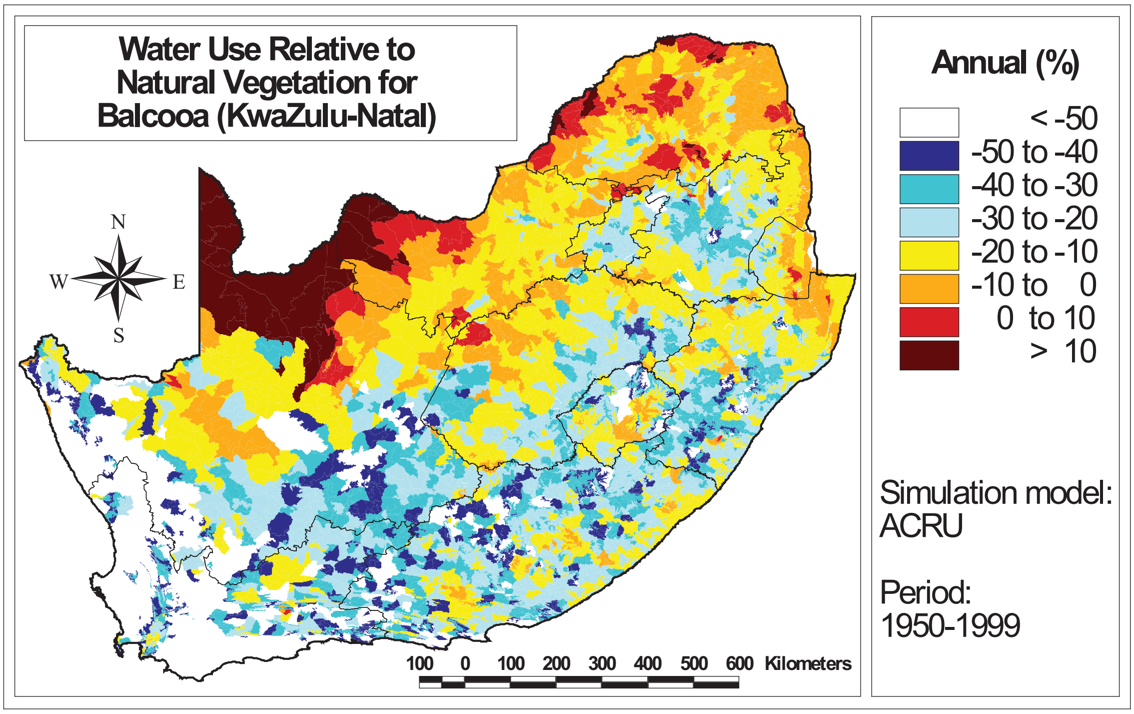
Beema (KwaZulu-Natal)

Figure 6-6: Funnel charts showing the difference in mean annual runoff produced from a land cover of bamboo (three scenarios) compared to natural vegetation

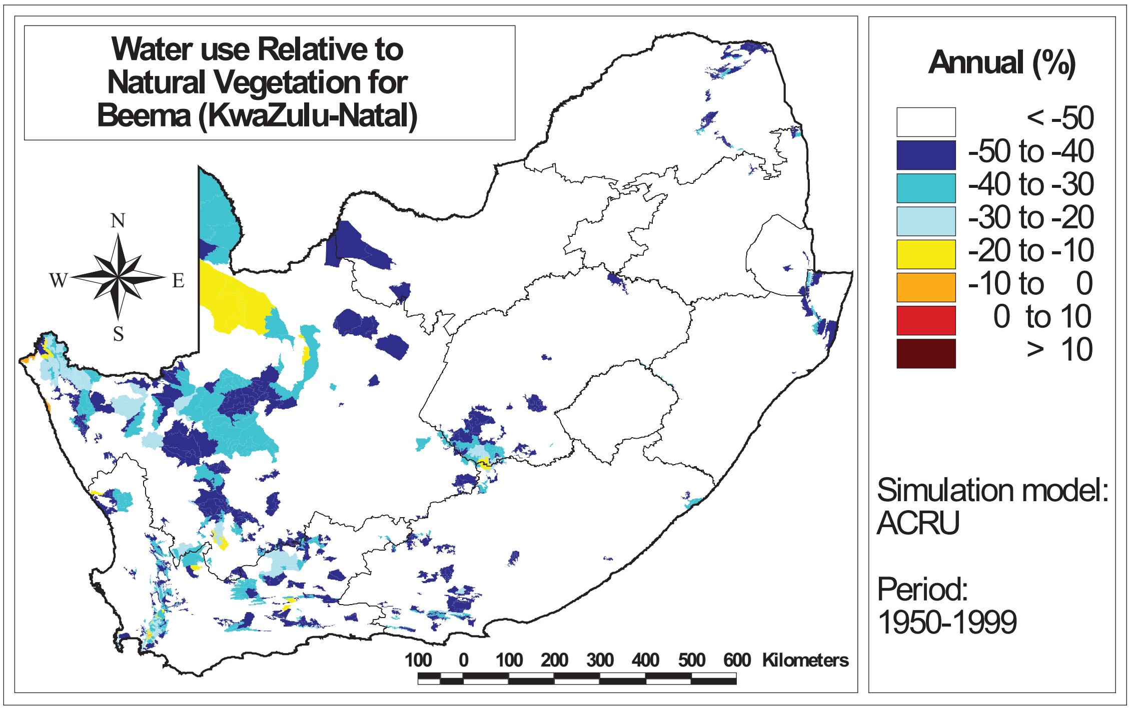
The simulated reduction in MAR can also be expressed as a percentage change, relative to the baseline runoff, i.e. $100 \cdot (MAR_{BASE} - MAR_{CROP})/MAR_{BASE}$. Figure 6-7 highlights the relative reduction in runoff that may result from a land cover change from natural vegetation to bamboo for the three scenarios. Reductions above 0% indicate that less runoff is produced from a land cover of natural vegetation than for bamboo land cover (i.e., $MAR_{BASE} > MAR_{CROP}$). For balcooa, this mainly occurs in the northern parts of the Northern Cape and North West, as well as in certain quinaries in Limpopo. It is evident that the KwaZulu-Natal scenario has a greater impact on runoff generation than the Eastern Cape scenario. For the beema (KwaZulu-Natal) scenario, simulated runoff production from bamboo was higher than from natural vegetation across all quinaries. Hence, the latter scenario has the least impact on downstream water availability.



Balcooa (Eastern Cape)



Balcooa (KwaZulu-Natal)



Beema (KwaZulu-Natal)

Figure 6-7: Water use of the three bamboo scenarios expressed as a relative percentage of the baseline

6.5.3 Stream flow reduction

If the relative impact on runoff exceeds 10%, the proposed land use change may be declared a SFRA (Jewitt et al., 2009). From Table 6-5, only 32 quinary subcatchments produced reductions greater than 10% for the KwaZulu-Natal scenario for balcooa, with the worst being ~ 36% (Quinary 2235). Similarly, the Eastern Cape scenario for balcooa exhibits SFRA potential in 18 quinaries, with the worst being ~ 31% in Quinary 2237. Using the 10% threshold, which is considered a significant reduction in MAR, the three bamboo scenarios can be ranked in terms of their potential to reduce water availability to downstream users as follows:

- Balcooa, KwaZulu-Natal (32 quinaries)
- Balcooa, Eastern Cape (18 quinaries)
- Beema, KwaZulu-Natal (0 quinaries)

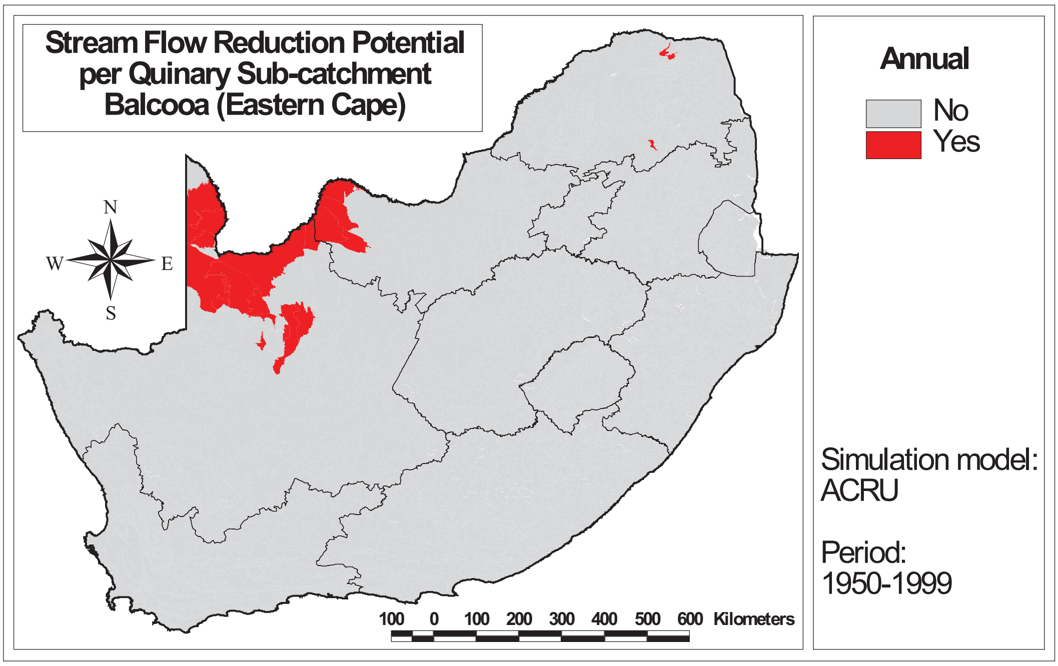
Although the relative reductions may exceed 10%, they are based on low absolute reductions in MAR (in mm), with the largest values being 5.0 and 6.3 mm (in Quinary 627) for the Eastern Cape and KwaZulu-Natal scenarios, respectively. Hence, the percentage changes are "amplified" by the low MAR produced in these quinaries, which results from the low subcatchment rainfall. For the worst-case scenario in terms of stream flow reduction potential (i.e. balcooa, KwaZulu-Natal), MAP across all 32 quinaries ranges from 146 to 488 mm. Commercial production of bamboo is unlikely to be viable in these quinaries with such low rainfall. This point becomes clearer when considering the location of these quinaries.

Table 6-5: Quinaries in which a relative reduction in mean annual runoff is 10% or more for balcooa

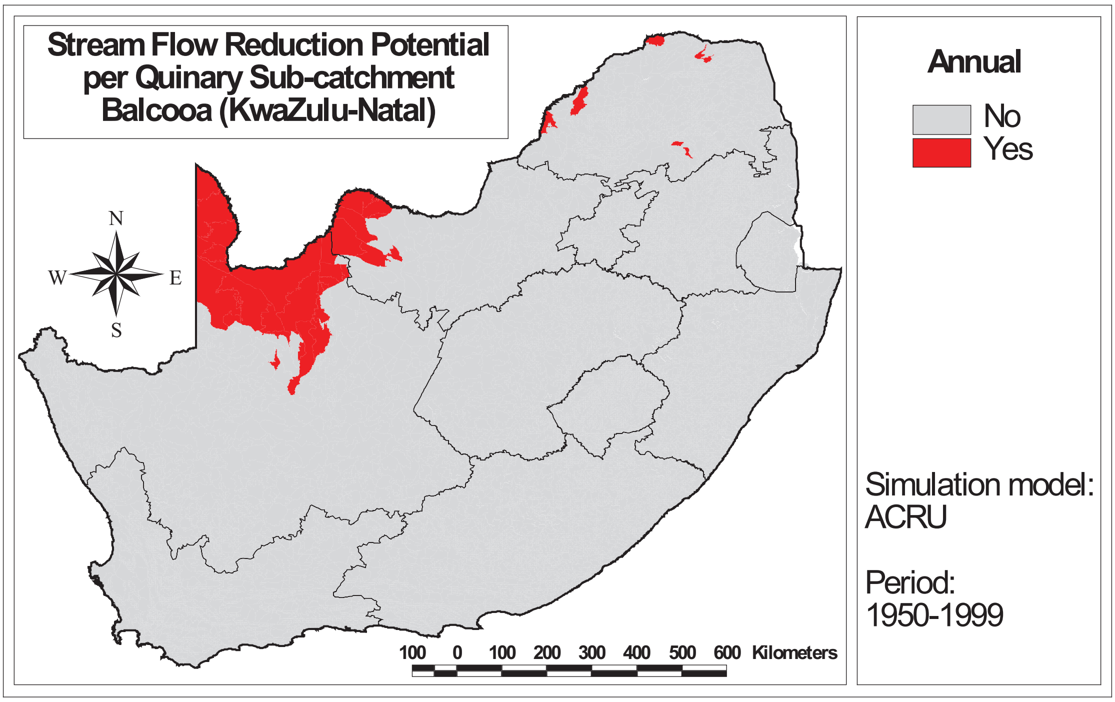
SUB_CAT	SFRA potential (1 = Yes; 0 = No)		Common (1 = Yes)	MAP (mm)	MAR reduction (mm)		MAR reduction (%)	
	Eastern Cape	KwaZulu-Natal			Eastern Cape	KwaZulu-Natal	Eastern Cape	KwaZulu-Natal
627	1	1	1	488	5.0	6.3	13.3	17.0
213	0	1		482	1.4	4.3	4.0	12.6
633	0	1		464	3.7	5.4	8.5	12.4
183	0	1		455	1.5	4.1	6.0	16.2
2206	0	1		397	2.6	4.6	8.4	14.8
309	0	1		350	0.8	2.6	3.4	10.5
2203	0	1		348	0.3	2.0	1.8	11.6
2204	0	1		340	1.1	2.4	8.4	18.0
2233	0	1		336	2.3	5.2	6.6	15.2
2213	1	1	1	323	2.9	3.6	12.0	14.7
2224	0	1		313	1.4	2.8	7.0	14.5
2205	1	1	1	309	1.7	2.2	18.7	24.8
2226	0	1		308	1.3	2.6	8.6	17.8
2208	1	1	1	303	2.1	2.8	18.2	24.5
2225	0	1		303	1.2	2.5	8.4	17.5
2018	1	1	1	300	1.8	2.6	11.1	16.1

SUB_ CAT	SFRA potential (1 = Yes; 0 = No)		Common (1 = Yes)	MAP (mm)	MAR reduction (mm)		MAR reduction (%)	
	Eastern Cape	KwaZulu-Natal			Eastern Cape	KwaZulu-Natal	Eastern Cape	KwaZulu-Natal
2214	1	1	1	294	2.6	3.3	14.0	17.6
368	1	1	1	276	1.2	1.7	12.6	18.1
2234	0	1		267	1.0	2.2	9.1	19.9
2020	1	1	1	263	4.3	5.0	12.8	15.0
2227	0	1		229	1.8	3.2	7.4	13.2
2023	1	1	1	213	1.7	2.5	10.4	14.8
2019	1	1	1	212	1.1	1.3	24.0	29.2
2235	1	1	1	210	1.5	2.0	27.2	36.1
2228	1	1	1	209	1.9	3.2	10.5	17.8
2229	1	1	1	189	1.7	2.7	13.1	20.4
2236	1	1	1	187	2.0	2.6	19.0	24.9
2231	1	1	1	173	1.7	2.3	18.0	24.3
2230	1	1	1	172	1.8	2.4	20.2	26.1
2232	0	1		170	0.8	1.5	6.9	13.2
2237	1	1	1	168	2.6	2.6	31.3	31.8
2238	1	1	1	146	1.7	1.8	26.1	26.7
Total	**18**	**32**	**18**					

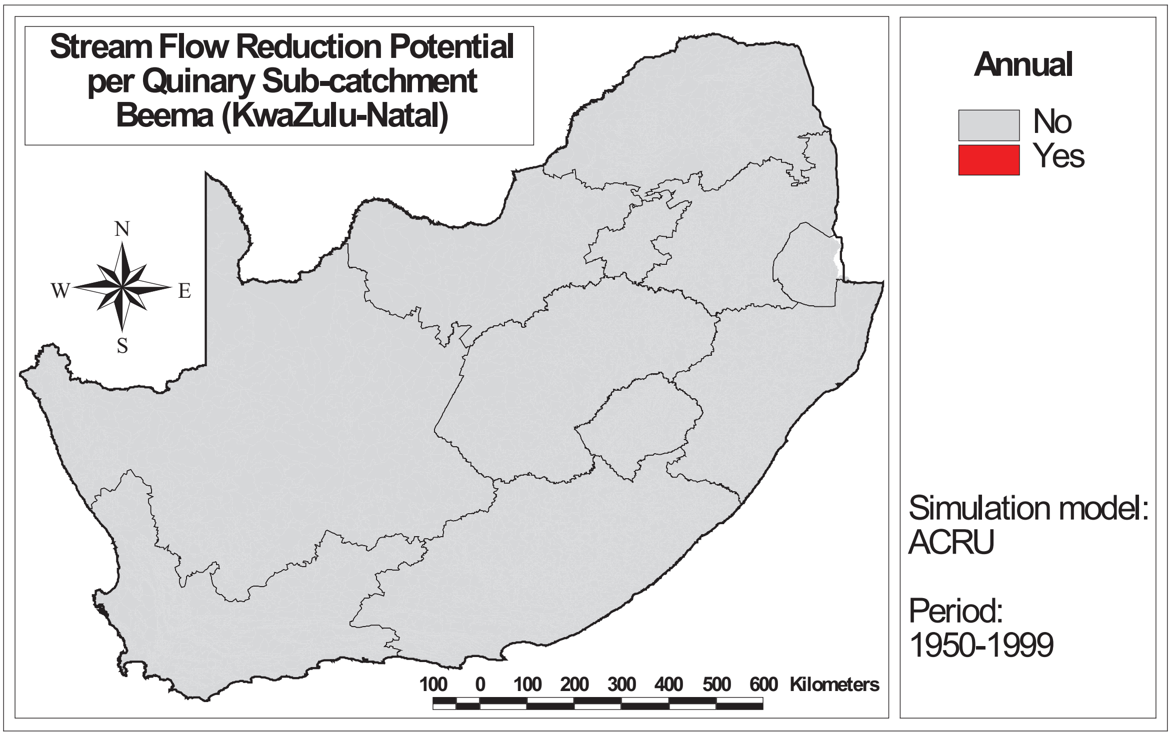
The quinaries coloured red in Figure 6-8 exhibit more than a 10% reduction in runoff that may result from a land use change to bamboo. As highlighted previously, these quinaries are mostly located along the northern border of South Africa. The quinaries that are located in the Northern Cape and North West are unlikely to support the rainfed production of bamboo due to their low rainfall and high reference crop evaporation.



Balcooa (Eastern Cape)



Balcooa (KwaZulu-Natal)

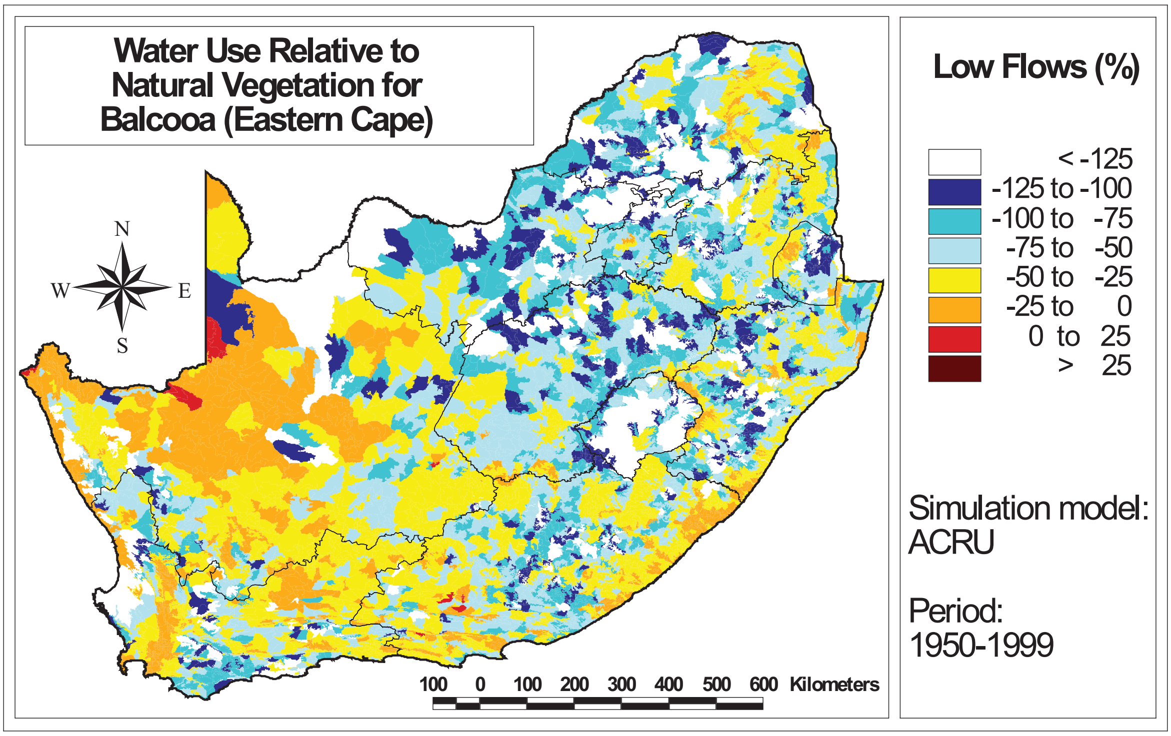


Beema (KwaZulu-Natal)

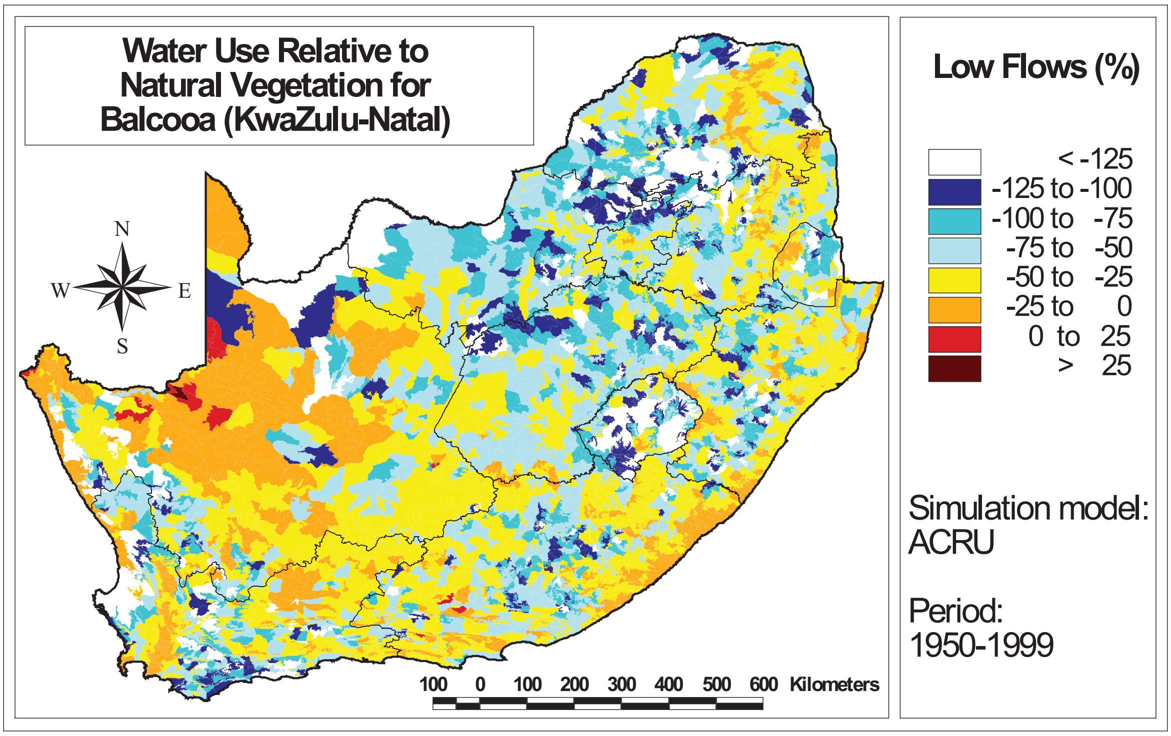
Figure 6-8: Subcatchments in which the reduction in mean annual runoff resulting from a land use change from natural vegetation to bamboo is 10% or more

6.5.4 Hydrological impact on low flows

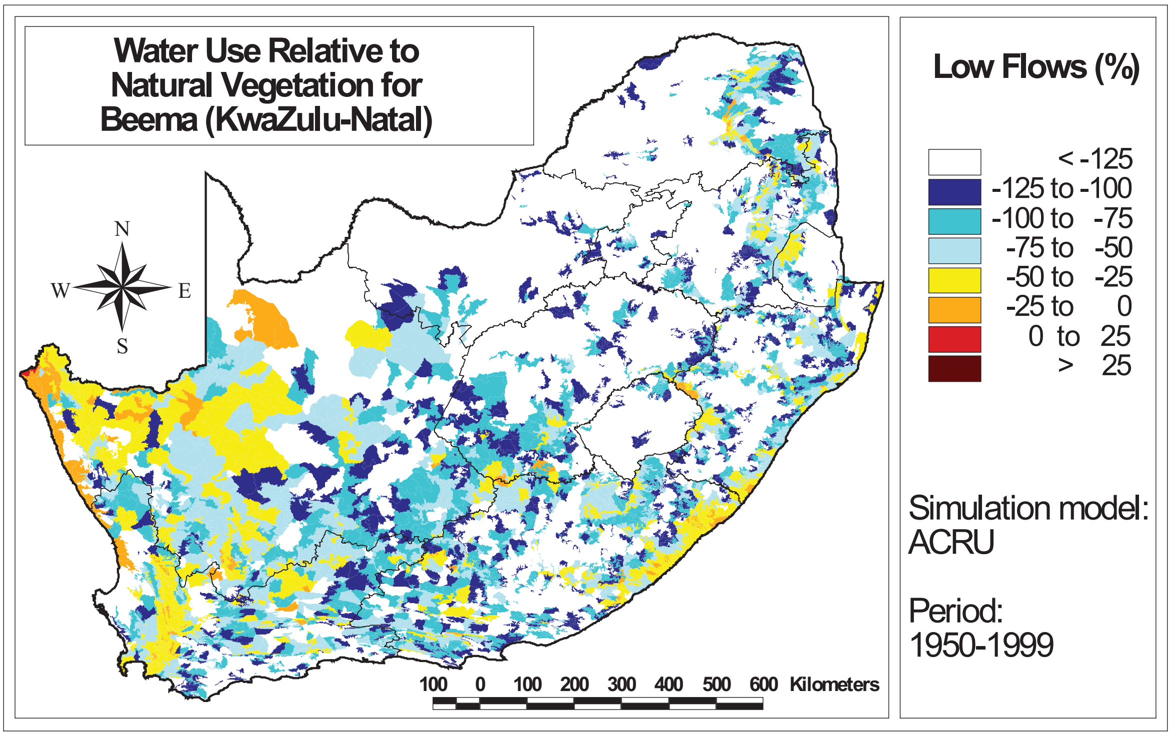
Scott and Smith (1997) highlighted the fact that stream flow reductions during low flow periods may be proportionately greater than for annual flows. Therefore, an assessment of bamboo's stream flow reduction potential during periods of low flow is considered important. Mean monthly flows were accumulated over the driest quartile (i.e. three months with the lowest runoff response) for the baseline, as well as for each bamboo species. The percentage difference (relative to the baseline) was then calculated. If it exceeds 25%, the reduction is considered significant, as recommended by Jewitt et al. (2009) (see Figure 4-1). From Figure 6-9, no quinaries exhibited a reduction in low flows that exceeds 25%.



Balcooa (Eastern Cape)



Balcooa (KwaZulu-Natal)



Beema (KwaZulu-Natal)

Figure 6-9: Subcatchments in which the reduction in mean monthly low flows that results from a land use change from natural vegetation to bamboo is 25% or larger

6.6 SFRA ASSESSMENT UTILITY

A PC-based software utility has been developed to disseminate stream flow output from the ACRU model, and to assess the impact on a land use change to bamboo cultivation on downstream water availability. It is envisaged that this utility will mainly be used by the Department of Human Settlements, Water and Sanitation to assess bamboo's stream flow reduction potential in any quinary subcatchment of South Africa. A brief overview of the utility is given in Section 6.6.1, which is adapted from WRC Project K5/2491 (Kunz et al., 2020) on the water use of biofuel crops, where a more complete description can be obtained.

This utility represents an update of the original versions (version 1.02 and 1.04) that were developed as part of the SFRA project (Jewitt et al., 2009). The utility underwent significant changes to create version 2.00 as part of WRC project K5/1874 on the water use of biofuel crops (Kunz et al., 2015). This is explained in more detail in Section 6.2.2. The utility allows users to extract estimates of water use for different land uses at the quinary subcatchment scale, and then to assess the potential reduction in stream flow against the baseline land use (i.e. natural vegetation). In this bamboo project, three land use scenarios were considered: balcooa (Eastern Cape), balcooa (KwaZulu-Natal) and beema (KwaZulu-Natal).

6.6.1 Overview of the utility

The assessment utility has a user-friendly interface, which allows the user to select a particular quinary subcatchment. It then zooms into the area (or subcatchment) of interest. Next, the user selects the baseline land use (typically natural vegetation), as well as the proposed land use (e.g. bamboo). The utility then displays monthly time series of simulated runoff (i.e. *SIMSQ*) generated under baseline conditions and the proposed land use.

These two time series can be displayed in both tabular and graphic form, the latter producing a plot that helps to visualise the difference in runoff generated by the two land uses. In essence, the utility provides a time series of ACRU model output, while performing the various calculations.

Crop water use is defined as the reduction in stream flow that may result from a land use change from the baseline to bamboo. The simulated stream flow reduction (i.e., $MAR_{BASE} - MAR_{CROP}$) is computed and easily exported to a spreadsheet if necessary. Estimates of stream flow reductions can also be viewed as monthly or annual flow duration curves for user-selected time periods. The change in *SIMSQ* (mm) is plotted against the probability of exceedance, with low flows defined as those falling below the 75th percentile exceedance level. Various statistics can also be calculated (and exported) for the subcatchment.

In terms of the current SFR legislation, the user selects the appropriate baseline land cover, which for bamboo is based on 121 vegetation clusters that were developed in WRC Project K5/2437, "Resetting the baseline land cover against which stream flow reduction activities and the hydrological impacts of land use change are assessed" (Warburton Toucher et al., 2019). Hence, stream flow reductions are assessed relative to the runoff generated under pristine or natural conditions.

6.6.2 Improvements made to utility

A number of improvements were made to version 1.0 of the biofuel's assessment utility. Since then, the utility has undergone a major revision to version 2.0. The most significant changes to the utility are briefly described. It is worth noting that the utility is currently being further developed to accommodate various other WRC-funded projects.

6.6.2.1 ACRU BIN files

For the SFRA project, the output from the ACRU model (daily stream flow or *SIMSQ* values) was stored in a structured database. This involved the conversion of ACRU's binary output files for multiple quinaries into a single data "blob". Although this process simplified the packaging (and retrieval) of information by the SFRA utility, it significantly increased the post-processing time. For version 2.0, the utility was modified to read ACRU's output (i.e. BIN) files directly in their raw binary (non-ASCII) format. This improvement negated the need to re-format ACRU's output, thus significantly reducing the time required to update the utility's database.

6.6.2.2 Exclusion of arid areas

Since arid areas are generally unsuited to crop growth and water use that would likely be considered as SFRAs, it is logical to exclude such areas. An MAP threshold of 250 mm was selected as the absolute minimum annual rainfall required for dryland farming, which resulted in the exclusion of 820 quinaries.

6.6.2.3 Default options

A number of default options are set in the utility for the user's convenience:

- The utility initially displays all quinaries exhibiting an MAP ≥ 250 mm.
- The baseline land use is set to 121 vegetation clusters defined by Warburton Toucher et al. (2019).
- The *ACRU* output variable is set to simulated stream flow (i.e. *SIMSQ*), which excludes all upstream contributions.

6.6.2.4 Inclusion of other variables

The calculation of statistics, which the utility performs "on-the-fly", was modified to accommodate other ACRU output variables where daily values are either aggregated (i.e. summed) into monthly totals (e.g. rainfall) or averaged to monthly values (e.g. crop coefficients).

6.6.2.5 Start of the hydrological year

Statistics have been calculated with October as the start of the hydrological year (and not January as the start of a calendar year). In the summer rainfall region of South Africa, annual statistics calculated from October to September (and not January to December) are more intuitive from a hydrological viewpoint.

6.6.2.6 Installation issues

A Microsoft Access database file was originally used by the utility to link the quinary number (e.g. 0010) to its name (e.g. A21A1), as well as to manage the list of proposed land uses for which data is available. This utility required a driver to access the database file, which caused installation problems on certain PCs. This database file was converted to XML format, which negated the need to use the specialised driver, thus simplifying the installation of the utility on any PC.

6.6.2.7 Batch export

The batch export utility was re-written to improve the speed of extracting data from the ACRU binary (.BIN) file and re-formatting it to a more user-friendly comma separated (.CSV) file format. Only the mean statistic is output at present.

6.7 SUMMARY OF MODELLING OUTCOMES

Based on the results presented in Section 6.6, rainfed production of bamboo does not appear to negatively impact downstream water availability to any great extent. Therefore, this land use is unlikely to be declared a potential stream flow reduction activity by the Department Human Settlements, Water and Sanitation.

CHAPTER 7: DISCUSSION

The water use of bamboo is not well understood under South African climatic conditions. Therefore, the evapotranspiration of important species of bamboo required quantification in South Africa to provide a scientific basis to decide on the status of this crop as a stream flow reduction activity. Daily and seasonal sap flows at Shooter's Hill in KwaZulu-Natal and at EcoPlanet in the Eastern Cape were measured to provide water use estimates of *Bambusa balcooa* var. beema and *Bambusa balcooa* var. balcooa. This was important to determine the impact of planting bamboo on water resources.

One of the concerns about the impact of bamboo is that its high growth rate could result in high water use. It was therefore necessary to quantify the growth of bamboo in this study. While in-depth growth studies (e.g. culm height development, biomass accumulation and carbon storage) were beyond the scope of this project, pilot studies were carried out to determine the increase in the number of culms and the increase in culm diameter. This information was used to scale-up the water use data from a single plant to a plantation.

The results from KwaZulu-Natal showed that, during the study period, there was an increase in the total number of bamboo culms in both the beema and balcooa plantations. In the beema plantation, there was an 18% increase in the number of culms, with an additional 38 beema culms (February 2020) from the initial 213 culms measured in September 2018. There was also a 10% increase in the beema culm diameter (10%) from a mean of 34.0 ± 5.6 mm (September 2018) to a mean of 37.4 ± 9.5 mm (February 2020). This low increase translated to 0.2 mm month^{-1}. In the balcooa clumps, there was a 12.5% increase in culms, with an additional seven bamboo culms from the initial 56 culms measured in September 2018. The balcooa bamboo culms had a lower increase in diameter (2.6%) from 77.30 ± 14.49 mm in September 2018 to 79.33 ± 14.91 mm in February 2020 (0.12 mm month^{-1}).

By contrast, a decrease in growth was initially recorded in the Eastern Cape, although the difference was not significant. During the 17-month study in the Eastern Cape, the mean culm diameter on 7 February 2019 (19.28 ± 8.69 mm) decreased to 16.74 ± 6.39 mm on 12 November 2019 due to the death of some of the culms. At the end of the study on 12 August 2020, the mean culm diameter was 19.37 mm, resulting in a mean growth rate of only 0.005 mm month^{-1}. The high standard deviations indicate the variability of the culms measured. The difference in growth between the two sites was also supported by the contrasting frequency in size classes of the culm diameters. The data at KwaZulu-Natal had a normal distribution, with 54% of the 246 culms measured falling into the 30–49 mm size class. The data in the Eastern Cape also had a normal distribution, but less than 1% of the culms fell into the 30–49 mm size class. Most stems (51%) fell into 10–19 mm size class.

The low increase in culm diameter supports Thapa and Aryal (2012), who stated that the culm diameter remains constant during or after the elongation period. However, these authors reported that, in *B. balcooa,* the culms produced in subsequent years were distinctly wider in diameter than those produced in the previous years, and that this trend continued up to the clump age of seven years. This indicates that future growth studies should be long term and include more growth parameters, such as culm height and biomass.

The reason for the greater culm size classes and growth in the bamboo growing in KwaZulu-Natal when compared to that growing in the Eastern Cape may be attributed to the differences in rainfall between the two sites. In KwaZulu-Natal, rainfall was high during the 2018/19 hydrological year (September 2018 to October 2019) when 1 304.9 mm was recorded at the site. A further 799.6 mm was recorded for the period from November 2019 to mid-February 2020. With a total of 2 104.5 mm for the 17-month study period, the KwaZulu-Natal site was considered "wet".

The growth recorded in other studies supports these findings. For example, in the Gujarat state of India, where the average annual rainfall was 1 055 mm, the culm diameter at breast height of *Bambusa balcooa* was 41.4 mm (Amlani et al., 2017). Contrasting the overlapping 17-month measurement periods in the two provinces (November 2019 to May 2020) showed that KwaZulu-Natal had 2 065 mm of rainfall compared with only 652 mm recorded in the Eastern Cape. The Eastern Cape site was therefore considered "dry". In the Eastern Cape, the annual rainfall for 2019 and 2020 was only 412 and 481 mm, respectively. This was approximately 200 mm lower than the long-term average of 690 mm, illustrating the extent of the drought in the Eastern Cape. Another reason for the differences in growth parameters between the two study sites may be soil conditions. The Eastern Cape site had previously been subject to monocropping pineapples, which likely resulted in impoverished soil conditions.

The increase in bamboo growth culm diameter (0.5–10.0%) was significantly lower than that of the wattle trees, which had a 41.3% increase in average stem diameter from 116 mm (September 2018) to 164 mm (January 2020). The estimated growth rates of these trees were 3.0–4.0 mm monthly. Similarly, growth in the eucalyptus trees was high with a 46.6% increase in stem diameter from the initial average stem diameter (103 mm) recorded in April 2019, compared with the final measurement of 151 mm in January 2020. The eucalyptus growth therefore increased monthly at a rate of 5.4 mm, which was significantly higher than the growth rate of bamboo (0.005 to 0.2 mm month^{-1}).

Rainfall had a significant impact on the soil water content in KwaZulu-Natal. With high summer rainfall, the total soil water profile content in the KwaZulu-Natal bamboo plantation was ~ 180 mm, with > 70 mm measured in the shallower depths (0–200 mm). When rainfall decreased from 152.7 mm in April 2019 to 7.4 mm in June 2019, the total soil water content declined to ≤ 100 mm with a shallow-depth soil water content of less than 45 mm. In the Eastern Cape, the reduction in total soil water content from 170 mm in May 2019 to under 80 mm in November 2019 was associated with a decrease in rainfall from 68 mm in May 2019 to a low of 14 mm in December 2019.

Daily water use data of both bamboo species measured using the HPV and SSS methods in KwaZulu-Natal showed similar diurnal trends in the dry winter and wet summer. A positive correlation (R^2 = 0.78 for beema and R^2 = 0.87 for balcooa) between water use measured with both systems for a three-month period of summer data (January to March 2019) supported these observations. Similar results were also found in a study by Dierick et al. (2010), where the water use data of *Bambusa blumeana,* measured with the HPV and SSS methods, showed slight differences. It was assumed that position differences between the systems affected the results. Since the correlation between the transpiration data using the different sap flow methods was high in this study for compiling the longer-term annual data, conclusions were derived from the average data collected from both systems, as this provided a better continuous temporal data series.

In KwaZulu-Natal, the daily water use in the beema plantation was 2.0 ± 3.2 mm day^{-1} in the wet summer and 1.0 ± 1.6 mm day^{-1} in the dry winter, respectively. Beema culms transpired twice as much in summer compared to winter, due to the limiting moisture and energy in the cold season. Conversely, water use in the balcooa clump showed a range of 3.8 ± 6.0 mm day^{-1} in the wet summer, whereas 2.0 ± 2.8 mm day^{-1} was recorded in the dry winter. Therefore, the water use in balcooa was twice that of the beema plantation under similar climatic conditions. These results suggested that the larger culm diameters of balcooa (a giant bamboo) resulted in a higher water use compared with the smaller beema plants. This was supported by the anatomical study, where a higher number of vascular bundles was recorded per mm of culm (46.6 vascular bundles) when compared to beema (25.9 vascular bundles).

In KwaZulu-Natal, the water use of bamboo was closely related to climatic conditions. During the hydrological year (October 2018 to September 2019), the total rainfall recorded was 1 217.2 mm with high rainfall over 20.0 mm day^{-1} recorded in summer (November to March 2019), High rainfall and high temperatures (> 32.0 ^{o}C) resulted in maximum transpiration rates in the bamboo plantations at this time.

For example, in February 2019, when the maximum temperature was 32.9 ^{o}C and monthly rainfalls reached ~ 230.6 mm, transpiration of the balcooa and beema plantations was ~ 6.0 and > 2.5 mm day^{-1}, respectively. By contrast, a total winter rainfall of only 37.4 mm was recorded from May to June 2019 with temperatures under 18.0 ^{o}C, resulting in low transpiration rates. For example, when the total rainfall and average temperature recorded in July 2019 was 1.3 mm and 17.6 ^{o}C, the low average daily transpiration in the balcooa clump and beema plantation was ~ 2.4 mm day^{-1} and < 2.0 mm day^{-1}, respectively. This showed the effect of seasonal climatic conditions in controlling the rates of bamboo transpiration in KwaZulu-Natal. This data also suggested that bamboo (a grass) was behaving in a similar manner as natural grassland, in that it is a conservative water user during winter. The annual water use of balcooa and beema was 746 and 510 mm, respectively. Maximum daily ET rates measured for balcooa in the Eastern Cape were only 3 mm day^{-1} in the summer, contrasting markedly with the KwaZulu-Natal land use values, which were generally double (6.0 mm day^{-1}). In the Eastern Cape, the annual total evaporation was only 446 and 567 mm for the 2019 and 2020 years, respectively. This was indicative of the dry climate brought about by the severe drought experienced in the Eastern Cape during the study.

The water use of the selected bamboo species was compared with the other land uses at Shooter's Hill: eucalyptus and black wattle plantations. This data was compared with the reference evaporation data collected in the nearby grassland to estimate crop factors.

In the wet summer, peak daily water use in the eucalyptus plantation was ~ 8.0 mm, when energy, temperature and rainfall were high (Figure 5-24). This was significantly higher than the daily bamboo water use (2–3.3 mm). The results also showed that eucalyptus trees were using > 2.0 mm day^{-1} more soil water compared with the balcooa plantation. By contrast, in winter, the eucalyptus transpiration rates were reaching ~ 4.0 mm day^{-1}, with an average daily water use of ~ 3.0 mm, especially from June to July 2019 (Figure 5.24).

Van Lill et al. (1980) also recorded high water use in eucalyptus trees in a long-term monitoring study conducted in the subtropical Mpumalanga. The study showed high seasonal water use in the three-year-old eucalyptus trees, reaching 260 mm in the wet summer and 130 mm in the dry winter. To make this data comparable on a daily basis, it was interpreted to show that eucalyptus trees constantly transpired > 3.0 mm day^{-1} in summer. A similar study was conducted by Albaugh et al. (2013) in South Africa, who reported that the water use in three-year-old eucalyptus trees was 7.0 mm day^{-1} in the wet summer and 2.2 mm day^{-1} in the dry winter. Therefore, high summer and low winter transpiration in these studies supported the water use estimates measured in the eucalyptus trees at Shooter's Hill.

Water use measured in the black wattle trees showed that the maximum summer transpiration was higher than that of the bamboo plantations (~ 5.0 mm day^{-1}). This was also the case in winter, when transpiration rates of > 3.0 mm day^{-1} were recorded, with peak winter transpiration rates of ~ 3.5 mm day^{-1} (Figure 5-28). With less differences in water use across the different seasons, transpiration rates were considered similar in all seasons.

Other studies of upland black wattle plantation water use conducted in the Mistley-Canema Estate (Mondi forests), KwaZulu-Natal, showed high daily total transpiration ~ 8.0 mm in summer using the Bowen ratio energy balance system (Dye & Jarmain, 2004). Clulow et al. (2011) also estimated high daily summer water use reaching 9.0 mm and 2.2–2.4 mm in winter using a large aperture scintillometery in two-and-a-half-year-old wattle trees in the Mistley-Canema Estate. Summer transpiration rates measured in these studies were 4.0 mm higher than the water use measured at Shooter's Hill, which was lower than expected. The low values measured in this study are likely due to competition and shading from the surrounding dense beema culms.

The maximum water use of bamboo can be modelled by multiplying the calculated ET_0 by a crop coefficient, K_c. Measured daily evaporation and reference evaporation (ET_0) were used to calculate monthly crop coefficients for each land use. This provided useful comparisons of the bamboo species with the other land uses. The K_c values for bamboo were a major input for the ACRU SFRA modelling exercise used for assessing the SFRA status of bamboo under South African climatic conditions (Chapter 6).

The summer daily transpiration values showed that the average K_c in the beema plantation was ~ 0.40 in the wet summer season and 0.49 in the dry winter season. Therefore, the data showed that the beema plantation had a much lower transpiration rate than the reference evaporation at Shooter's Hill, indicating that it can be considered a conservative water user.

Similarly, in the 15-month recording period, the monthly K_c values recorded for balcooa were < 1. By contrast, the higher K_c values for eucalyptus (0.65–1.07) and wattle (0.55–1.28) (Table 5-5) indicated that they were higher water users than bamboo. In the black wattle trees, high monthly K_c values, reaching 1.04, were recorded in winter, when estimated transpiration rates were higher than ET_0. For example, in July 2019, the transpiration recorded in the black wattle trees was 72.9 mm, whereas ET_0 was 58.9, showing the high water use of the black wattle trees in the dry period compared to ET_0. Conversely, the average summer K_c was 0.79 (Table 5-4). These results showed high water use estimates in winter and low water use estimates in summer when compared to the ET_0.

The quantification of the water use of balcooa, beema, eucalyptus and wattle in KwaZulu-Natal and the Eastern Cape has shown that bamboo was a more conservative water user than eucalyptus or wattle. The results provided a unique data set that was used to determine whether bamboo should be classified as a SFRA for three potential scenarios:

- Balcooa (Eastern Cape)
- Balcooa (KwaZulu-Natal)
- Beema (KwaZulu-Natal)

Reductions in runoff that may result from a land cover change from natural vegetation to bamboo for these three scenarios indicated that less runoff was produced from a land cover of natural vegetation than for bamboo (i.e. $MAR_{BASE} < MAR_{CROP}$). For balcooa, this mainly occurs in the northern parts of the Northern Cape and North West, as well as in certain quinaries in Limpopo. It is evident that the KwaZulu-Natal scenario has a greater impact on runoff generation than the Eastern Cape scenario. For the beema (KwaZulu-Natal) scenario, simulated runoff production from bamboo was higher than that from natural vegetation across all quinaries. Hence, the latter scenario has the least impact on downstream water availability.

If the relative impact on runoff exceeds 10%, the proposed land use change may be declared a SFRA (Jewitt et al., 2009). In this study, only 32 quinary subcatchments out of a total of 5 838 produced reductions greater than 10% for the KwaZulu-Natal scenario for balcooa, with the worst being ~ 36% (Quinary 2235). Similarly, the Eastern Cape scenario for balcooa exhibits SFRA potential in 18 quinaries, with the worst being ~ 31% in Quinary 2237. Using the 10% threshold, which is considered a significant reduction in MAR, the three bamboo scenarios can be ranked in terms of their potential to reduce water availability to downstream users as follows:

- Balcooa, KwaZulu-Natal (32 quinaries)
- Balcooa, Eastern Cape (18 quinaries)
- Beema, KwaZulu-Natal (0 quinaries)

Therefore, when applied to the total number of quinaries in South Africa (5 838), balcooa was considered a SFRA in only 0.5% of the quinaries, while beema was not considered a SFRA. Although the relative reductions may exceed 10%, they are based on low absolute reductions in MAR (in mm), with the largest values being 5.0 and 6.3 mm (in Quinary 627) for the Eastern Cape and KwaZulu-Natal scenarios, respectively. Hence, the percentage changes are amplified by the low MAR produced in these quinaries, which results from the low subcatchment rainfall. For the worst-case scenario in terms of stream flow reduction potential (i.e. balcooa, KwaZulu-Natal), MAP across all 32 quinaries ranges from 146 to 488 mm. Commercial production of bamboo is unlikely to be viable in these quinaries with such low rainfall. This point becomes clearer when considering the location of these quinaries.

CHAPTER 8: CONCLUSION

The main objective of this study was to determine the evapotranspiration and stream flow reduction impact of bamboo species in South Africa. Although bamboo species are reported to have a high growth rate, which implies that they are high water users, this was not the case in the current study. The growth of bamboo was significantly lower than the growth of black wattle and eucalyptus trees. Growth was closely related to rainfall, with no significant growth occurring in the drought-stricken area of the Eastern Cape in comparison to KwaZulu-Natal.

One of the first steps in measuring the evapotranspiration of bamboo (which is a woody grass species), was to select appropriate techniques to measure water use. This was achieved by testing the HPV technique against the SSS method, where a good correlation was found between them. This enabled the combination of the two data sets to obtain a more reliable estimate of bamboo transpiration.

Since no previous studies on the water use of bamboo have been carried out in South Africa, it was necessary to carry out anatomical studies on the two bamboo varieties (beema and balcooa) selected for this study. The results showed how the vascular bundles are arranged in the tissue with respect to their radial position in the culm, which enabled the positioning of the HPV probes at the appropriate depths and for calculating the sap flow area for scaling-up to the whole plant.

The HPV and SSS techniques were selected to measure the water use of bamboo for a period of 12 to 18 months. The results showed that transpiration rates of at least 1.0 mm day^{-1} in winter and 2.0 mm day^{-1} in summer occurred in the beema plantation. On the other hand, more than 2.0 mm day^{-1} and 3.8 mm day^{-1} were measured in the balcooa plantation in winter and summer, respectively.

The comparative studies between the bamboo species and the neighbouring commercial forest species, such as eucalyptus and black wattle, and natural grassland, revealed that the bamboo species were more conservative water users. Black wattle and eucalyptus trees had a comparatively higher water use, exceeding 2.0 mm day^{-1} in winter, and reaching 5.0 to 8.0 mm day^{-1} in summer. By contrast, beema in the Eastern Cape had a very low water use (maximum rates of daily transpiration ~ 2.5 mm) when compared with all other land uses. The crop coefficient data generated in this study provided a benchmark of how three-year-old bamboo species used water compared to the reference evaporation. The results showed that bamboo species were using at least 40% less water compared to reference evaporation and there were also large differences when compared to other land uses, such as eucalyptus and black wattle trees in terms of their conservative water use. These results provided a unique data set that was used to determine whether bamboo should be determined a SFRA.

If the relative impact on runoff exceeds 10%, the proposed land use change may be declared a SFRA. When this threshold was applied to three scenarios (balcooa planted in KwaZulu-Natal, balcooa planted in the Eastern Cape, and beema planted in KwaZulu-Natal), balcooa was considered a SFRA in less than 0.5% of the quinaries, while beema was not considered a SFRA at all. Therefore, the commercial production of these two clumping bamboo species would be expected to have a minimal impact on stream flow.

CHAPTER 9: REFERENCES

ACOCKS JPH (1988) *Veld types of southern Africa*. Botanical Survey of South Africa Memoirs 57, Botanical Research Institute, Pretoria, South Africa.

ALBAUGH JM, DYE PJ and KING JS (2013) Eucalyptus and water use in South Africa. International Journal of Forestry Research **1** 1–11.

ALLEN RG, PEREIRA LS, RAES D and SMITH M (1998) *Crop evapotranspiration. Guidelines for computing crop water requirements.* FAO Irrigation and drainage paper 56, FAO, Rome, Italy.

AMLANI M, TANDEL M, PRAJAPATI V, PATHAK J and BEHERA L (2017) Assessment of growth variation among different species of Bamboo. International Journal of Chemical Studies **5** 1436–1439.

ANGUS GR (1989) Sensitivity of ACRU model input. In: *ACRU: Background: Concepts and theory*, SCHULZE RE. WRC Report No. 154/1/89, Water Research Commission, Pretoria, South Africa.

AWALLUDDIN D, ARIFFIN MAM, OSMAN MH, HUSSIN MW, ISMAIL MA, LEE H-S and LIM NHAS (2017) Mechanical properties of different bamboo species. MATEC Web of Conferences 2017, EDP Sciences.

BAMBOO BOTANICALS (2019) Bamboo anatomy and growth habits. Bamboo botanicals. http://www.bamboobotanicals.ca/html/about-bamboo/bamboo-growth-habits.html (Accessed 23 November 2020).

BAYONA-RODRÍGUEZ CJ and ROMERO HM (2016) Estimation of transpiration in oil palm (Elaeis guineensis Jacq.) with the heat ratio method. Agronomía Colombiana **34** 172–178.

BEBBINGTON AJ, BEBBINGTON DH, SAULS LA, ROGAN J, AGRAWAL S, GAMBOA C, IMHOF A, JOHNSON K, ROSA H and ROYO A (2018) Resource extraction and infrastructure threaten forest cover and community rights. Proceedings of the National Academy of Sciences **115** 13164–13173.

BRANTLEY CG and PLATT SG (2001) Canebrake conservation in the southeastern United States. Wildlife Society Bulletin **29** 1175–1181.

BREDA NJ (2003) Ground-based measurements of leaf area index: A review of methods, instruments and current controversies. Journal of Experimental Botany **54** 2403–2417.

BULCOCK HH and JEWITT GPW (2012) Modelling canopy and litter interception in commercial forest plantations in South Africa using the variable storage Gash model and idealised drying curves. Hydrology and Earth Systems Science **16** 4693–4705.

BURGESS SS, ADAMS MA, TURNER NC, BEVERLY CR, ONG CK, KHAN AA and BLEBY TM (2001) An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiology **21** 589–598.

BURGESS SS, ADAMS MA, TURNER NC and ONG CK (1998) The redistribution of soil water by tree root systems. Oecologia **115** 306–311.

BUSANI B (2011) Bamboo use "could help stop Africa's deforestation". Sci Dev Net: Bringing science and development together through news and analysis. Sci Dev Net Magazine **11** (6 December).

CENTRE OF AGRICULTURAL AND BIOSCIENCE INTERNATIONAL (CABI) (2019) Bambusa bambos (giant thorny bamboo). *Invasive Species Compendium*, Centre of Agriculture and Bioscience International, Wallingford, UK.

CANAVAN S, RICHARDSON DM, VISSER V, LE ROUX JJ, VORONTSOVA MS and WILSON JR (2017) The global distribution of bamboos: Assessing correlates of introduction and invasion. AoB Plants **9** 1–18.

CHANDRAMOULI S and VISWANATH S (2012) Bamboo shoots – an emerging new age health food. Forestry Bulletin **12** 21–28.

CHAPMAN RD (2004) *Estimation of vapour pressure and solar radiation in South Africa*. MSc dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

CHEN S, JIANG H, CAI Z, ZHOU X and PENG C (2018) The response of the net primary production of Moso bamboo forest to the on and off-year management: A case study in Anji County, Zhejiang, China. Forest Ecology and Management **409** 1–7.

CIRTAIN MC (2004) Effects of nitrogen and moisture regimes on Arundinaria gigantea (Walt.) Nuhl. seedling growth. Natural Areas Journal **24** 251–257.

CIRTAIN MC, FRANKLIN SB and PEZESHKI SR (2009) Effect of light intensity on Arundinaria gigantea growth and physiology. Castanea **74** 236–246.

CLULOW A, EVERSON C and GUSH M (2011) *The long-term impact of Acacia mearnsii trees on evaporation, streamflow and ground water resources*. WRC Report No. TT505/11, Water Research Commission, Pretoria, South Africa.

DAS M, GOPAKUMAR B, SHAMEENA M, JERO-MATHU A, NATH A and DAS A (2017) Floral biology and pollen sterility in relation to seed set in Bambusa balcooa. Journal of Tropical Forest Science **29** 504–508.

DATTILO AJ and RHOADES CC (2005) Establishment of the woody grass Arundinaria gigantea for riparian restoration. Restoration Ecology **13** 616–622.

DIERICK D, HÖLSCHER D and SCHWENDENMANN L (2010) Water use characteristics of a bamboo species (Bambusa blumeana) in the Philippines. Agricultural and Forest Meteorology **150** 1568–1578.

DUNBAR G (2018) *Commercial bamboo farming: A local solution to a global problem.* South Africa Brightfields. http://www.brightfields.co.za/bamboo-farming (Accessed 8 March 2019).

DYE P and JARMAIN C (2004) Water use by black wattle (Acacia mearnsii): Implications for the link between removal of invading trees and catchment streamflow response: Working for Water. South African Journal of Science **100** 40–44.

DZVUKAMANJA TN, GÖRGENS AHM and JONKER V (2005) *Streamflow reduction modelling in water resource analysis.* WRC Report No. 1221/1/05, Water Research Commission, Pretoria, South Africa.

ECOPLANET BAMBOO (2018). EcoPlanet Bamboo Group. https://s3-us-west-2.amazonaws.com/ungc-production/attachments/cop_2019/474093/original/EcoPlanet_Bamboo_COP_2018.pdf?1556778147. (Accessed 8 March 2019).

EVETT SR, TOLK JA and HOWELL TA (2006) Soil profile water content determination. Vadose Zone Journal **5** 894–907.

FATRIASARI W, SYAFII W, WISTARA N, SYAMSU K and PRASETYA B (2014) The characteristic changes of betung bamboo (Dendrocalamus asper) pretreated by fungal pretreatment. International Journal of Renewable Energy Development **3** 133–143.

FELISBERTO MHF, BERALDO AL and CLERICI MTPS (2017) Young bamboo culm flour of Dendrocalamus asper: Technological properties for food applications. LWT-Food Science and Technology **76** 230–235.

GASH JH, LLOYD CR and LACHAUD G (1995) Estimating sparse forest rainfall interception with an analytical model. Journal of Hydrology **170 (1–4)** 79–86.

GUANGLU L (1988) Analysis and investigation on the structure of rhizome system of bamboo forests. Journal of Bamboo Research **7** 35–44.

GUPTA A and KUMAR A (2008) Potential of bamboo in sustainable development. Asia Pacific Business Review **4** 100–107.

GUSH M (2008) Measurement of water use by Jatropha curcas L. using the heat-pulse velocity technique. Water SA **34** 579–584.

HOGG EH, BLACK TA, DEN HARTOG G, NEUMANN HH, ZIMMERMANN R, HURDLE PA, BLANKEN PD, NESIC Z, YANG PC and STAEBLER RM (1997) A comparison of sap flow and eddy fluxes of water vapor from a boreal deciduous forest. Journal of Geophysical Research: Atmospheres **102** 28929–28937.

HUGHES TP, BAIRD AH, BELLWOOD DR, CARD M, CONNOLLY SR, FOLKE C, GROSBERG R, HOEGH-GULDBERG O, JACKSON JB and KLEYPAS J (2003) Climate change, human impacts, and the resilience of coral reefs. Science **301** 929–933.

JEWITT GPW, LORENTZ SA, GUSH MB, THORNTON-DIBB S, KONGO V, WILES L, BLIGHT J, STUART-HILL SI, VERSFELD D and TOMLINSON K (2009) *Methods and guidelines for the licensing of SFRAs with particular reference to low flows.* WRC Report No. 1428/1/09, Water Research Commission, Pretoria, South Africa

JORDAN CF (1969) Derivation of leaf-area index from quality of light on the forest floor. Ecology **50** 663–666.

KAUSHAL R, SINGH I, THAPLIYAL SD, GUPTA AK, MANDAL D, TOMAR JMS, KUMAR A, ALAM NM, KADAM D, SINGH DV and MEHTA H (2020) Rooting behaviour and soil properties in different bamboo species of Western Himalayan foothills, India. Scientific Reports **10 (1)** 1–17.

KELLENERS T, SEYFRIED M, BLONQUIST J, BILSKIE J and CHANDLER DG (2005) Improved interpretation of water content reflectometer measurements in soils. Soil Science Society of America Journal **69** 1684–1690.

KLEINHENZ V and MIDMORE D (2000) Estimating water usage of bamboo. Access to Asian Vegetables **28** 1–2.

KOMATSU H, ONOZAWA Y, KUME T, TSURUTA K, KUMAGAI TO, SHINOHARA Y and OTSUKI K (2010) Stand-scale transpiration estimates in a Moso bamboo forest: II. Comparison with coniferous forests. Forest Ecology and Management **260** 1295–1302.

KOSHY K, HARIKUMAR D and NARENDRAN T (2001) Insect visits to some bamboos of the Western Ghats, India. Current Science 833–838.

KRAYESKY DM and CHMIELEWSKI JG (2014). Arundinaria gigantea: New to Pennsylvania. Rhodora **116** 228–231.

KRUGER AC, RETIEF JV and GOLIGER AM (2013) Strong winds in South Africa: Part 2 Mapping of updated statistics. International Journal of Renewable Energy Development **55 (2)** 46–58..

KUMAR B, RAJESH G and SUDHEESH K (2006). Aboveground biomass production and nutrient uptake of thorny bamboo [Bambusa bambos (L.) Voss] in the homegardens of Thrissur, Kerala. Journal of Tropical Agriculture **43** 51–56.

KUNZ RP, DAVIS NS, THORNTON-DIBB SLC, STEYN JM, DU TOIT ES and JEWITT GPW (2015) *Assessment of biofuel feedstock production in South Africa: Atlas of water use and yield of biofuel crops in suitable growing areas.* Volume 3. WRC Report No. TT 652/15, Water Research Commission, Pretoria, South Africa.

KUNZ R, MASANGANISE J, REDDY K, MABHAUDHI T, LEMBEDE L, NAIKEN V and FERRER S (2020) *Water use and yield of soybean and grain sorghum for biofuel production.* WRC Report No. 2491/1/20, Water Research Commission, Pretoria, South Africa.

LAHR FAR, JUNIOR HS and FIORELLI J (2015) *Non-conventional building materials based on agro-industrial wastes,* Tiliform, Bauru, Brazil. https://www.researchgate.net/publication/276900038_Non-conventional_Building_Materials_based_on_Agro-industrial_Wastes.

LAPLACE S, KOMATSU H, TSENG H and KUME T (2017) Difference between the transpiration rates of Moso bamboo (Phyllostachys pubescens) and Japanese cedar (Cryptomeria japonica) forests in a subtropical climate in Taiwan. Ecological Research **32** 835–843.

LASCANO RJ, GOEBEL TS, BOOKER J, BAKER JT and GITZ III DC (2016). The stem heat balance method to measure transpiration: Evaluation of a new sensor. Agricultural Sciences **7** 604–620.

LI J, ZHENG H, SUN Q, HAN S, FAN B, YAO Q, YAN C and JIN C (2015) Fabrication of superhydrophobic bamboo timber based on an anatase TiO 2 film for acid rain protection and flame retardancy. Royal Society of Chemistry Advances **5** 62265–62272.

LIU C-G, WANG Q-W, JIN Y-Q, PAN K-W and WANG Y-J (2017) Photoprotective and antioxidative mechanisms against oxidative damage in Fargesia rufa subjected to drought and salinity. Functional Plant Biology **44** 302–311.

LIU C, WANG Y, PAN K, JIN Y, LI W and ZHANG L (2015) Effects of phosphorus application on photosynthetic carbon and nitrogen metabolism, water use efficiency and growth of dwarf bamboo (Fargesia rufa) subjected to water deficit. Plant Physiology and Biochemistry **96** 20–28.

LOWE RJ, PIVAN X, FALTER J, SYMONDS G and GRUBER R (2016) Rising sea levels will reduce extreme temperature variations in tide-dominated reef habitats. Science Advances **2** e1600825.

LU P and CHACKO E (1998) Evaluation of Granier's sap flux sensor in young mango trees. Agronomie, **18** 461–471.

LU P, URBAN L and ZHAO P (2004) Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: Theory and practice. Acta Botanica Sinica **46** 631–646.

MARSHALL D (1958) Measurement of sap flow in conifers by heat transport. Plant Physiology **33** 385–396.

MCMICHAEL AJ, WOODRUFF RE and HALES S (2006) Climate change and human health: Present and future risks. The Lancet **367** 859–869.

MUHAMMAD HNJ (2018) *Evaporation, transpiration and evapotranspiration.* Forestrypedia. https://forestrypedia.com/evaporation-transpiration-and-evapotranspiration/ (Accessed 24 November 2020).

MULKEY SS (1986) Photosynthetic acclimation and water use efficiency of three species of understory herbaceous bamboo (Gramineae) in Panama. Oecologia **70** 514–519.

NEAL D, BALDWIN B, ERVIN G, JOLLEY R, CAMPBELL J, CIRTAIN M, SEYMOUR J and NEAL J (2012) Assessment of seed storage alternatives for rivercane (Arundinaria gigantea). Seed Technology **34** 119–126.

NEGI D and SAXENA S (2011) Micropropagation of Bambusa balcooa Roxb. through axillary shoot proliferation. In Vitro Cellular and Developmental Biology – Plant **47** 604–610.

NURUL FAZITA M, JAYARAMAN K, BHATTACHARYYA D, MOHAMAD HAAFIZ M, SAURABH CK, HUSSIN MH and HPS AK (2016) Green composites made of bamboo fabric and poly (lactic) acid for packaging applications – a review. Materials **9** 435.

ONOZAWA Y, CHIWA M, KOMATSU H and OTSUKI K (2009) Rainfall interception in a moso bamboo (Phyllostachys pubescens) forest. Journal of Forest Research **14 (2)** 111–116.

PERDRIAL J, SULLIVAN PL, DERE A and WEST N (2020) Critical Zone (CZ) Export to streams as indicator for CZ structure and function. Frontiers in Earth Science **25** 1–3.

PULAVARTY A and SARANGI BK (2018) Screening bamboo species for salt tolerance using growth parameters, physiological response and osmolytes accumulation as effective indicators. Chemistry and Ecology **34** 340–354.

RAY S and ALI M (2016) Evaluation of inexpensive bedding materials for culm cutting of Bambusa balcooa Roxb. and its field performance. Journal of Biotechnology and Biomaterials **6** 1–6.

SAVAGE M, GRAHAM A and LIGHTBODY K (1993) Use of a stem steady state heat energy balance technique for the in situ measurement of transpiration in Eucalyptus grandis: Theory and errors. South African Journal of Science – Horticultural Sciences **3** 46–51.

SAVAGE MJ, GRAHAM A and LIGHTBODY KE (2000). *An investigation of the stem steady state heat energy balance technique in determining water use by trees.* WRC Report No. TT505/11, Water Research Commission, Pretoria, South Africa.

SAVVA AP and FRENKEN K (2002) *Crop water requirements and irrigation scheduling.* FAO Sub-Regional Office for East and Southern Africa Harare.

SCHEBA A, MAYEKI S and BLANCHARD R (2018) Bamboo for green development in South Africa? **16,** 20–22.

SCHMIDT J, LARNED S, ARSCOTT D and DIETTRICH J (2009) Hydrological indices for quantifying ecologically relevant flow conditions in intermittent alluvial plain rivers. International Association of Hydrological Science Publication **20** 94–102.

SCHRÖDER S (2007) *Bambusa bambos.* https://www.guaduabamboo.com/blog/bambusa-bambos (Accessed 26 November 2020).

SCHULZE RE (1995) *Hydrology and agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system.* WRC Report No. TT 69/9/95, Water Research Commission, Pretoria, South Africa.

SCHULZE RE (2004) Determination of baseline land cover variables for applications in assessing land use impacts on hydrological responses in South Africa. In: *Development and evaluation of an installed hydrological modelling system*, SCHULZE RE and PIKE A. WRC Report No. 1155/1/04, Water Research Commission, Pretoria, South Africa.

SCHULZE RE (2007) Relative humidity: General background. In: *South African atlas of climatology and agrohydrology*, SCHULZE RE. WRC Report No. 1489/1/06, Water Research Commission, Pretoria, South Africa.

SCHULZE RE and CHAPMAN RD (2007) Estimation of daily solar radiation over South Africa. In: *South African atlas of climatology and agrohydrology*, SCHULZE RE. WRC Report No. 1489/1/07, Water Research Commission, Pretoria, South Africa.

SCOTT DF and SMITH RE (1997) Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. Water SA **23 (2)** 135–140.

SEETHALAKSHMI K, JIJEESH C and BALAGOPALAN M (2009) *Bamboo plantations: An approach to carbon sequestration. National workshop on global warming and its implications for Kerala*. Department of Forests and Wildlife, Kerala Forest Research institute and Bamboo Development Agency, Thiruvananthapuram, Kerala, India.

SETTE JR CR, DE CASTRO P, FREITAS VP, YAMAJI FM and DE ARAÚJO ALMEIDA R (2016) Production and characterization of bamboo pellets. Bioscience Journal **32** 992–930.

SHARMA P and SARMA K (2011) In vitro propagation of Bambusa balcooa for a better environment. International Conference on Advances in Biotechnology and Pharmaceutical Sciences, Planetary Scientific Research Centre, Bangkok, Thailand.

SHINOHARA Y, KOMATSU H, KURAMOTO K and OTSUKI K (2013) Characteristics of canopy interception loss in Moso bamboo forests of Japan. Hydrological Processes **27** 2041–2047.

SHROTI R, UPADHYAY R, NIRATKAR C and SINGH M (2012) Micropropagation of Dendrocalamus asper through inter nodal segment. Bulletin of Environment, Pharmacology and Life Science **1** 58–60.

SINGH SR, DALAL S, SINGH R, DHAWAN A and KALIA RK (2012) Micropropagation of Dendrocalamus asper: An exotic edible bamboo. Journal of Plant Biochemistry and Biotechnology **21** 220–228.

SMITHERS JC and SCHULZE RE (1995) *ACRU agrohydrological modelling system: User manual*, version 3.00. WRC Report No. TT 70/95, Water Research Commission, Pretoria, South Africa.

SUJARWO W, ARINASA I and PENENG I (2015) Biomass content of black Petung bamboo. Bamboo Journal **1** 36–39.

THAPA HB, and ARYAL R (2012) *Growth performance and culms production of some bamboo species in the mid- and- far-western Terai of Nepal.* Department of Forest Research and Survey, Babarmahal, Kathmandu.

TRUONG AH and LE TMA (2014) *Overview of bamboo biomass for energy production.* https://halshs.archives-ouvertes.fr/halshs-01100209/document. (Accessed 8 March 2019.

TSURUTA K, OKUMURA M, KUME T, ICHIHASHI R, SHINOHARA Y and KOSUGI Y (2016) Insignificant effects of culm age on transpiration in a managed Moso bamboo forest, Kyoto, Japan. Hydrological Research Letters **10** 1–7.

UPRETI T and SUNDRIYAL R (2001) Bamboo and cane resources of Arunachal Pradesh: Utilization pattern and implications for management. Bamboo Science and Culture **15** 20–34.

VAN LILL W, KRUGER F and VAN WYK D (1980) The effect of afforestation with Eucalyptus grandis Hill ex Maiden and Pinus patula Schlecht. et Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. Journal of Hydrology **48** 107–118.

VAUPEL F (2005) *Bambus Informationszentrum Online Pflanzenshop*. Fargesia of Robusta 'Campbell'. https://www.bambuspflanzen.de/.

VELLAME LM, COELHO FILHO MA, PAZ VP and COELHO EF (2010) Stem heat balance method to estimate transpiration of young orange and mango plants. Revista Brasileira de Engenharia Agrícola e Ambiental **14** 594–599.

VIANA PL and FILGUEIRAS TS (2014) Three new species of Aulonemia (Poaceae: Bambusoideae) from the Brazilian Atlantic rainforest. Phytotaxa **156** 235–249.

VON HOYNINGEN-HUENE J (1981) *The interception of precipitation in agricultural*. Work report German Association for Water, Wastewater and Agriculture, DVWK, Braunschwig, Germany.

VON HOYNINGEN-HUENE J (1983) *Die Interzeption des Niederschlages in landwirtschaftlichen Pflanzenbeständen.* Deutscher Verband für Wasserwirtschaft und Kulturbau. Schriften **57** 1–66.

WANG X, REN H, ZHANG B, FEI B and BURGERT I (2012). Cell wall structure and formation of maturing fibres of Moso bamboo (Phyllostachys pubescens) increase buckling resistance. Journal of the Royal Society Interface **9** 988–996.

WARBURTON TOUCHER ML, RAMJEAWON M, MCNAMARA MA, ROUGET M, BULCOCK H, KUNZ RP, MOONSAMY J, MENGISTU M, NAIDOO T and VATHER T (2019) Resetting the baseline land cover against which stream flow reduction activities and the hydrological impacts of land use change are assessed. Draft report for WRC Project No. K5/2437, Water Research Commission, Pretoria, South Africa.

XU Q-F, LIANG C-F, CHEN J-H, LI Y-C, QIN H and FUHRMANN JJ (2020) Rapid bamboo invasion (expansion) and its effects on biodiversity and soil processes. Global Ecology and Conservation **21** 1–10.

YANG S-J, ZHANG Y-J., GOLDSTEIN G, SUN M, MA R-Y and CAO K-F (2015) Determinants of water circulation in a woody bamboo species: Afternoon use and night-time recharge of culm water storage. Tree physiology **35** 964–974.

YING W, JIN J, JIANG H, ZHANG X, LU X, CHEN X and ZHANG J (2016) Satellite-based detection of bamboo expansion over the past 30 years in Mount Tianmushan, China. International Journal of Remote Sensing **37** 2908–2922.

APPENDIX A

CAPACITY BUILDING AND TECHNOLOGY TRANSFER

The capacity building and technology transfer activities included the scientific training of students for postgraduate qualifications through the registration of students at the University of KwaZulu-Natal. The following table indicates the students who have completed their qualifications, as well as those who are in the process of completing them.

Full name of student as specified on ID or passport (no student cards)	Student ID or Passport No.	Student Registration No.	Gender	Race	Qualification	Status	Name of community	Email address
Mxolisi Gumede	9101046070089	212501618	Male	Black	MSc	Completed	KwaDlangezwa	gumede_mp@yahoo.com
Shanice Ivy Chetty	9611220480086	215034078	Female	Indian	MSc	Ongoing	Pietermaritzburg	215034078@ukzn.ac.za

MP GUMEDE, MSc

Water use of commercial bamboo species in KwaZulu-Natal, South Africa

ABSTRACT

With the increasing impacts of global climate change, the depletion of natural resources and increased degradation of the world's environment, there is a need for more sustainable development. One such innovation is to convert degraded land into viable bamboo plantations, which will provide timber and fuel to achieve sustainable development. With its very fast growth rate, high productivity and tensile strength, bamboo also has the potential to reduce the deforestation of South Africa's natural forests. However, the bamboo species that have the most potential to solve South Africa's fuelwood crisis are not indigenous and the water use is not well understood under South African climatic conditions. Therefore, this study was conducted to quantify the water use of two commercial bamboo species: *Bambusa balcooa* var. balcooa and *Bambusa balcooa* var. beema in KwaZulu-Natal, with the water use of nearby *Eucalyptus grandis* and *Acacia mearnsii* plantations also quantified for comparison. Two different sap flow measuring techniques were used to quantify the water use of bamboo to determine their impact on water resources: the heat pulse velocity technique, which quantifies sap flow with respect to depth of temperature probes in a stem, and the stem steady state technique, which involves the application of continuous heat energy all around the stem through dynamax collars, which are used to quantify the total sap passing through a fixed area on a stem. The daily water use in the beema, balcooa, eucalyptus and black wattle plantation was 2.0 ± 3.2 mm day^{-1}, 3.8 ± 6.0 mm day^{-1}, ~ 8.0 mm day^{-1} and ~ 5.0 mm day^{-1}, respectively, in summer (the wet season), whereas 1.0 ± 1.6 mm day^{-1}, 2.0 ± 2.8 mm day^{-1}, ~ 4.0 mm day^{-1} and > 3.0 mm day^{-1}, respectively was recorded in winter (the dry season). This data demonstrated the low water use of bamboo species when compared to eucalyptus and black wattle plantations. While the hydrological modelling of bamboo as a stream flow reduction activity was beyond the scope of the current study, the determination of the crop factor (K_c) values was a critical component of this process. Therefore, the average K_c in the beema plantation was ~ 0.50 in the wet summer season and 0.67 in the dry winter season. Likewise, K_c values recorded for balcooa were < 1. By contrast, the higher K_c values for eucalyptus (1.03–1.80) and black wattle (0.52–1.47) indicated that eucalyptus and black wattle plantation were higher water users than bamboo.

SI CHETTY MSc

Estimating the water use of bamboo using satellite earth observation data

SUMMARY AND PROGRESS UPDATE FOR THE WRC BAMBOO PROJECT

In recent years, bamboo-derived products have taken on added significance in Africa as a renewable resource to produce greener energy and building global capacity in climate mitigation and adaptation strategies (Scheba et al., 2018). Internationally, bamboo plantations have been considered a substitute for forest plantations as bamboo has similar properties to that of timber when used for construction and various other socio-economic activities, but it is more desirable due to the significantly shorter growing periods and higher yields (Atanda, 2015). These plantations assist with the land restoration of degraded land and play a fundamental role in preventing deforestation (Atanda, 2015; Scheba et al., 2018).

Biomass (particularly firewood) serves as South Africa's traditional source of energy and timber. The national demand for this biomass far exceeds the available resources, and therefore resulted in intensive and extensive harvesting, subsequently leading to land degradation, poor water infiltration, severe erosion and loss of biodiversity. Given the economic and ecological benefits of these plantations, bamboo provides a possible option to curtail South Africa's biomass crisis; and is leaning towards the commercialisation due to its contribution to sustainable development.

The implications of bamboo plantations in South Africa have not yet been extensively researched.

- There is still pending knowledge regarding biodiversity loss should commercialisation commence.
- Invasiveness: the bamboo species under consideration are not indigenous to South Africa.
- Bamboo’s water consumption is not yet clear in a South African context.

The focus of this study would be the water use of bamboo plantations. Bamboo is a fast-growing evergreen, and research therefore needs to determine the following:

- If it would significantly reduce the quantity of water resources relative to the baseline.
- If it can be considered a stream flow reduction activity.
- Should there be a significant impact on water resources, what legislation will need to be amended or updated to allow commercialisation of this activity?

Therefore, understanding the spatio-temporal water use dynamics would prove to be invaluable in informing legislation governing the establishment of these plantations, and improving their management.

In the past, *in situ* techniques were the most commonly applied methods of estimating actual evapotranspiration (ET). While, these methods may prove ideal over small homogenous areas, it only offers point- or line-averaged estimates. There are several limitations of *in situ* approaches when regional applications of ET estimates are required.

Within the last four decades, the use of SEO (satellite earth observation) data has received increased attention as an alternate approach for the estimation of ET over large spatio-temporal scales. Where conventional *in situ* data is available as a validation tool, satellite data provides a suitable opportunity for the large-scale application of ET estimation. However, several limiting factors may alter the reliability of this data. These include the trade-offs between spatial and temporal resolutions (Courault et al., 2005; Ramoelo et al., 2014).

The overall aim of this study is to estimate the water use of bamboo plantations in South Africa. This will assist in informing water resources managers and practitioners about the feasibility of legislating bamboo plantations for commercial use.

For this purpose, the project will attempt to establish the feasibility of utilising finer spatio-temporal resolution imagery acquired from a Sentinel coupled with a satellite-based ET model for the localised mapping and estimation of ET to facilitate improved water resource management decisions.

The following specific objectives have been identified to fulfil the aim of this study:

- Gain an understanding of the water usage of bamboo plantations in a South African context using SEO data.
- Identify and apply an SEO-based approach to estimate bamboo water use at a sufficient spatio-temporal resolution.
- Identify and evaluate available methods to acquire high-resolution thermal data from Sentinel-2 imagery as input into a surface energy balance model.
- Validate or confirm the ET estimates produced by this approach against *in-situ*.
- Compare and contrast the water use dynamics of bamboo against some of the commonly used commercial afforestation species.

PROGRESS UPDATE

Both a literature review and a proposal were compiled and completed during the course of 2020. Research gaps have been identified and proposed methodologies have been considered to fill those gaps. The literature reviewed focused on the various approaches for estimating actual ET.

After a comprehensive review of various sources of literature and research, selection criteria were used to determine the most suitable method of ET estimation. This method identified as using SEO data, together with a method incorporating the use of the parameterisation of the energy balance equation. Given the availability of resources and the nature of study, the surface energy balance system was chosen to determine ET.

In addition to the aforementioned literature, various reports and documents of proposed bamboo plantations in South Africa were considered to contextualise this project and clearly identify the contribution of this project to national governance and legislation.

A research proposal was completed that summed up the main areas of focus based on the literature gaps. Various methodologies were proposed that could be ventured into. This included the *in-situ* methods employed at site, from which field measurements would be obtained, pre-processing and processing techniques for downloaded satellite images, performing different sharpening methods to obtain moderate to high spatiotemporal resolutions, and using a range of statistical analyses and multiple metrics as performance indicators to compare and contrast data from *in situ* to SEO ET.

In December 2020, the MSc defense presentation for this project was presented to academic staff and students of the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal. It was subsequently assessed by both the supervisor and co-supervisor, as well as a select number of examiners.

The data collection and analysis process has commenced. Satellite data is being downloaded. When an appropriate and representative date has been selected from cloud-free images, these images will undergo pre-processing techniques before applying data sharpening methods for input into the surface energy balance system.