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Sap Flow and Water Consumption of Captain Cook Tree [*Cascabela thevetia* (l.) Lippold].

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Abstract

A two-year field study documented the diurnal and nocturnal sap flow rates and water consumption of young (YCC), adult (ACC) and mature (MCC) Captain Cook trees [Cascabela thevetia (L.) Lippold] that were invading a riparian habitat in northern Queensland. For comparison, two native trees [black tea tree (Melaleuca bracteata F. Muell.) and Moreton Bay ash (Corymbia tessellaris (F.Muell.) K.D.Hill & L.A.S.Johnson)] growing in association with Captain Cook tree were also monitored. Sap flow measurements were grouped into eight timeframes per day (early morning, late morning, early afternoon, late afternoon, early night, late night, early dawn and late dawn).

Significant interactions in sap flow rate occurred between plant types, timeframes, and months. The magnitude of sap flow rate was Moreton Bay ash>YCC>ACC>black tea tree>MCC. Maximum sap flow rates tended to occur during early (1-3 pm) to mid-afternoon (4-6 pm) for all age groups of Captain Cook tree and the two native trees. Diurnal sap flow rates were significantly greater than nocturnal, and on a monthly basis sap flow rates were highest over the spring to autumn period (September-May) and lowest during winter (June–August).

Significant differences in water consumption also occurred between species and months. Water consumption peak time varied between plant types with most plants peaking in January except for MCC and Moreton Bay ash trees for which peak water consumption occurred in June and July respectively. Water consumption was high across all seasons except winter. The magnitude of water consumption was Moreton Bay ash>black tea tree>YCC>ACC>MCC trees. Moreton Bay ash registered maximal monthly water consumption (4700 L) compared with minimal consumption by MCC trees (55 L). On average, Captain Cook trees used 99% and 72% less water than Moreton Bay ash and black tea trees respectively.

The significantly lower water consumption by Captain Cook trees compared with Moreton Bay ash and black tea trees may be offset by high population densities. Results also suggest that knowledge of optimal sap flow timeframes may be advantageous in exploring optimal timing for application of control operations related to management of Captain Cook trees.

Keywords: Sap Flow Rate, Timeframes, Water Use, Yellow Oleander.

Summary text for Table of Contents: *Cascabela thevetia* (Captain Cook tree; yellow oleander) has become an invasive weed in northern Australia. The present study determined the daily and seasonal patterns of water use of young, adult, and mature Captain Cook tree to assist with decisions regarding optimal timing application of herbicides. Results suggest that optimal daily sap flow rates tended to occur during early to mid-afternoon for all age groups of Captain Cook tree and were highest over the spring to autumn period and lowest during winter in the dry tropics of northern Queensland.

Introduction

A thorough understanding of the biology and ecology of invasive weeds is necessary for their long-term management (Di Tomaso 2000) [1]. This includes not only an understanding of invasion dynamics associated with resource use, reproduction, growth, spread, and competitive interactions with other species but also the timing of management methods. For example, although applications of foliar spray, cut-stump, girdle, frill-"hack-n-squirt' and hatchet injection methods on woody vegetation in the USA can be made any time of the year, applications made during periods of heavy sap flow in spring may result in poor control (Randall 2013) [2]. Cascabela thevetia (L.) Lippold syn. *Thevetia peruviana* (Pers.) K.Schum, commonly known as Captain Cook tree or yellow oleander, is one of several invasive rangeland weeds reported in Australia and South Africa whose biology has been poorly understood (Grice and Martin 2005; Randall 2002; http://www.environment.co.za [3-6].

In Australia, Captain Cook tree has often been planted as an ornamental in domestic gardens and amenity situations. However, it has now escaped from these areas and formed large naturalised populations at several locations, particularly in northern Queensland (Department of Agriculture and Fisheries 2017) [7]. In recent years increased concerns about the spread and impacts of Captain Cook tree in northern Australia has resulted in the initiation of research to better understand its ecology and how to control it, particularly the timing of application of herbicides.

Captain Cook tree has significant impacts on both humans and the environment. For humans, most parts of the plant are toxic and, outside of Africa, human activities associated with livestock production are adversely impacted by Captain Cook tree through interference with grazing practices and increasing costs of managing and producing livestock [3, 8]. Reduction of ground cover in riparian areas in the dry tropics of northern Queensland is expected to adversely affect livestock production. Environmentally, Captain Cook tree not only shades out neighbouring plants but its litter is also toxic to other plants (Schmelzer 2006) [9]. For example, the germination of parthenium (*Parthenium hysterophorous*) is inhibited by Captain Cook tree (Pavithra et al. 2012) [10]. Infestations of Captain Cook tree can render riparian areas completely devoid of ground cover (Faiz Bebawi-personal observation).

To date, no information on the timing of application of herbicides in terms of best time of the year or day is available for Captain Cook tree. However, literature for other Australian woody weeds such as Lantana (*Lantana camara.*) is available. It is reported that the best time to spray Lantana is in the morning (before 10 a.m.) and in the afternoon (after 3 p.m.) as this is when the plant was found to be most susceptible to herbicides (Gladstone Regional Council 2017) [11]. This is because during the middle of the day the plant will close its pores (stomata) and reduce sap flow, thus reducing likelihood of herbicide entry and translocation. In addition, the best time of year for applying herbicide control to Lantana was found to be autumn when sap flows draw the poison down into the root stock and before night temperatures get too cold (Department of Agriculture and Fisheries 2016) [12]. Australian agriculture companies such as Dow Agro Sciences and Apparent Pty Ltd also list a clear restraint of not treating trees with poor sap flow on directions for use of herbicides (Dow Agrosciences 2017; Apparent Pty Ltd. 2017) [13, 14]. These companies re-enforce the directive to consider time of year and weather conditions as important factors that affect herbicide uptake and translocation.

Similar studies related to sap flow have been reported in the Northern hemisphere for unwanted shrub and tree vegetation (Randall 2013, Brant et al. 2014, Ferrell et al. 2015) [2, 15, 16]. Randall (2013) indicated that although 'Cut-stump, Girdle, Frill-Hack-n-Squirt, and Hatchet chemical injection treatment can be made any time of the year, application made during periods of heavy sap flow in spring may result in poor control of unwanted shrubs or trees. Ferrell et al. (2015) also showed that the efficacy of the Hack and Squirt herbicide application for woody plant control during spring, can be reduced because of heavy sap flow pushing the herbicide from the cut surfaces. In Europe, Brant et al. (2014) clearly demonstrated the applicability of the sap flow method for determining the effects of herbicides on plant transpiration of sunflower (*Helianthus annus*) plants.

Based on these reports, it is imperative that an integrated control program for Captain Cook tree should greatly benefit from information involving sap flow research related to timing of control. Consequently, the principal aim of the present study was to determine the daily and seasonal patterns of water use in terms of sap flow rate of three age groups young (YCC), adult (ACC) and mature (MCC) of the peach biotype of the introduced Captain Cook tree. We also included two native trees [black tea tree (*"Melaleuca bracteata" "Corymbia tessellaris"* F. Muell.) and Moreton Bay ash [Corymbia tessellaris (F.Muell.) K.D.Hill & L.A.S.Johnson] growing in association with Captain Cook tree at the field site for comparison. The findings are discussed in terms of the potential implications for the optimal timing of herbicide application by investigating herbicide control of Captain Cook tree as well as the role that infestations of Captain Cook tree may be playing in terms of water utilisation compared with native trees.

Materials and Methods

Study site, climate and vegetation

The study site (20 m × 30 m) was located in a riparian area (19º 49' S, 146º 33' E; elevation 250 m) c. 56 km east-northeast of Charters Towers in the dry tropics zone of northern Queensland, Australia. The soil type was a sandy clay loam (coarse sand 8.5%, fine sand 59%, silt 9% and Clay 27.8%) and the original vegetation comprised an open eucalypt woodland. In more recent years the shrub layer had become densely infested with a monoculture of the peach biotype of Captain Cook trees with an estimated population density of 63 000 plants ha-1. Native trees included narrow-leaved red ironbark (*Eucalyptus crebra* F.Muell.), Morton Bay ash and black tea tree. Population density of the Moreton Bay Ash and black tea trees was estimated at 50 plants ha-1 within the experimental site. The ground layer was devoid of any vegetation other than juvenile seedlings of Captain Cook tree.

A typical wet season occurs from November to April inclusive and accounts for c. 82% of the 659 mm mean annual rainfall (BOM 2013) [17]. This is followed by a relatively dry transitional period with occasional rainfall, lasting from May to October. Rainfall and evaporation data for Charters Towers during the study period is presented in [Table 1]. The difference between evaporation and rainfall during the summer months is demonstrated by the P/E (precipitation/evaporation) ratio (Floyd 2001) [18]. A ratio below the value of 1 demonstrates that evaporation is greater than rainfall.

In the present study, rainfall for the years 2009 to 2011 exceeded the long-term mean of 659 mm in all years by between 38, 42 and 71% respectively. During the summer period (December-February) in the years between 2009 and 2011, overall evaporation was less than rainfall compared with the rest of the year where evaporation was generally greater than rainfall [Table 1]. However, over all months and years, evaporation was greater than rainfall as indicated by the yearly P/E means [Table 1].

Table 1: Rainfall and Evaporation Data Charters Towers.

Month	Rainfall mm			Evaporation mm			P/E (precipitation/evaporation)		
	2009	2010	2011	2009	2010	2011	2009	2010	2011
J	357.9	137.9	181.7	149.2	189.8	187.2	2.40	0.73	0.97
F	382.2	213.2	149.0	130.2	145.8	161.6	2.93	1.46	0.92
M	12.4	76.7	218.9	192.0	160.6	136.6	0.06	0.48	1.60
A	72.9	31.2	71.1	155.0	122.6	139.4	0.47	0.25	0.51
M	23.0	9.8	26.7	124.4	124.8	131.0	0.18	0.08	0.20
J	0	5.3	32.0	115.8	109.2	105.0	0	0.05	0.30
J	0	7.4	3.5	130.4	117.2	115.0	0	0.06	0.03
A	0	95.0	1.3	163.8	131.8	152.6	0	0.73	0.01
S	0	57.2	0	201.2	155.4	188.0	0	0.37	0
O	0.1	68.7	23.5	262.0	196.4	215.4	0	0.35	0.11
N	19.9	182.6	20.4	251.4	162.6	237.2	0.08	1.12	0.09
D	70.4	244.4	182.0	280.0	155.4	206.8	0.25	1.57	0.88
Yearly	938.8	1129.4	910.1	2155.4	1771.6	1975.8	0.44	0.64	0.46

Experimental Design

A randomised block design using three replicates was used to determine sap flow rate and water consumption of five plant types: three age groups of Captain Cook trees, Moreton Bay Ash and black tea trees. The three age groups of Captain Cook trees were arbitrarily divided into young (YCC), adult (ACC) and mature (MCC) trees based on basal stem diameters of 6-9 cm, 10-13 cm and >18 cm respectively. The black tea tree and Moreton Bay ash basal diameters were between 6-9 cm and 40-45 cm respectively. Each of the selected trees were fitted with sensors to record sap flow rates and to allow calculation of water use.

Sap flow rate measurements

Sap flow was measured in this study using the Heat Ratio Method (HRM) as described in Burgess et al. 2001 [19]. Three small (1.3 mm diameter) needles were inserted into the water conducting tissue or sapwood of the tree. These being two measurement needles symmetrically arranged, 5 mm equidistance above and below a central heater. A pulse of heat delivered by the heater could then be traced in the acropedal and basipedal directions within the sap stream and a ratio of the temperature rise determined. This ratio being used to accurately determine, initially the raw heat pulse velocity, and then corrected for the manner in which heat moved through the woody matrix of each species based on their own specific thermal diffusivity and any possible response to wounding to give sap velocity (cm hr-1). The accurately measured corrected sap velocity then multiplied by the corresponding Sap Wood Area of each tree to yield Sap Flow (L hr-1).

HRM30 sensors were sourced from ICT International Pty. Ltd., Armidale NSW, Australia to measure sap flow. They consisted of three 35 mm long needles integrally connected to a 16-bit microprocessor. The top and bottom needles contained two thermistors located at 7.5 mm and 22.5 mm from the tip of each needle. The third and centrally located needle was a line heater that ran the full length of the needle to deliver a uniform pulse of heat through the sapwood. After discussion with the manufacturer, installation occurred on the main stem of plants 2 m above ground [Figure 1].

Figure 1: Sap flow sensor and microprocessor attached to stem of Captain Cook tree.

Prior to installation of the sensors, bark depth was determined. Any rough, lose or flaky bark was removed to provide a reference or datum point upon which to accurately determine the depth of placement of the radial measurement points of each needle. Using a drill guide secured to the datum point on the stem, care was taken to drill three parallel holes. Sensor needles were inserted making sure to insert each measurement point in the same depth of water conducting xylem or sapwood.

Petroleum jelly was then applied to the three needles to make them easier to insert and to maintain thermal contact between the needles and wood tissue (Barrett et al. 1995), with one sensor needle (downstream) inserted in the top hole, the heater in the middle and the second sensor needle (upstream) in the bottom hole [20]. The micro-processor was connected by a 3-wire power extension cable to a tree mounted IB16-WP Data Bus Hub (16 channel interface) which was connected to an SL5-1L Smart Logger. A wireless Maxon Next-G modem, connected to the smart logger provided wireless remote data access, with data downloaded monthly. Both the sensor needles and microprocessor units were protected from bird damage by wrapping rabbit wire around the stem and units.

Determination of water use

We used the Sap Flow Tool Software (ICT International Pty. Ltd., Armidale NSW Australia) to determine water use for the three age groups of Captain Cook tree and the two native species. Besides hourly sap flow velocity data, the software required input of wood properties of the selected plants. This included recording sapwood depth and xylem radius (sapwood + heartwood), which was determined at the end of the experiment near where the probes were located by taking a 30 cm long cross-sectional stem core using a ‘Haglof’ forestry 2 thread 300 mm increment borer (Haglof Sweden AB, Klockargatan 8, Langsele, Sweden). The extracted stem core was treated with 0.1% methyl orange indicator to visibly reveal the proportion of sapwood and heartwood. The sapwood stained yellow and the heartwood deep red (Kutscha and Sachs 1962) [21]. The sap and heartwood depth or thickness was then measured using a ruler. The values obtained were entered into the corresponding Sap Wood Area Outer and Inner input fields in the Sap Flow Tool Software, corresponding to the radial position of the inner and outer measurement points located in the water conducting xylem. Bark depth was also measured using a bark depth gauge and entered into the software [Table 2].

Table 2: Wood properties of the invasive peach biotype of Captain Cook tree [young (YCC), adult (ACC) and mature (MCC)] and the two native plants (Black tea tree and Moreton Bay Ash) used in the present study.

Wood properties	Cascabela thevetia age groups			Native species	
	Young (YCC)	Adult (ACC)	Mature (MCC)	Black tea tree	Moreton Bay Ash
Basal diameter (cm)	6-9	10-13	18-23	9	45
Bark depth (cm)	0.07	0.07	0.18	0.1	0.17
Sapwood depth (cm)	2.3	2.0	7.20	0.80	4.0
Heartwood diameter (cm)	0	0	0.55	3.01	38.5
Xylem radius (cm)	2.3	2.0	7.75	3.81	42.5
Green volume (cm3)	0.45	0.40	1.41	0.16	0.79
Moisture (%)	0.1	0.1	0.4	0.3	0.4

Data analysis

Downloaded sap velocity (cm hr-1) and processed sap flow (L hr-1) data of the five plant types was split into 8 daily time periods and analysed. The 8 daily timeframes included early morning (7 am -9 am), late morning (10 am–12 am), early afternoon (1 pm–3 pm), late afternoon (4 pm – 6 pm), early night (7 pm–9 pm), late night (10 pm – 12 pm), early dawn (1 am–3 am) and late dawn (4 am–6 am). Monthly water consumption was automatically calculated by the software Sap flow tool and was downloaded for statistical analysis of variance.

Results

Wood properties

Sapwood depth of YCC, ACC and MCC trees averaged 2.3 cm, 2.0 cm and 7.20 cm respectively compared with 0.8 and 4.0 cm for the black tea trees and Moreton Bay ash [Table 2]. Xylem radius (sapwood + heartwood depth) was lowest in both YCC and ACC trees, intermediate in the MCC trees and highest in Moreton Bay ash trees.

Sap flow rate

Significant interactions ($P<0.001$) in sap flow rates were detected between plant types and timeframes [Figure 2]. All plant types demonstrated a similar pattern of sap flow over the course of a day, but the rate varied, particularly during peak times. At the start of each day, sap flow remained consistently at its lowest until early morning (7-9 am). It then increased almost linearly before peaking in the early afternoon (1-3 pm) for all plant types. It continued to remain high during the mid-afternoon period, except for the ACC trees which declined significantly from early afternoon onwards. Sap flow of YCC and MCC trees, black tea tree and Moreton Bay ash all declined significantly from mid-afternoon onwards. By midnight sap flow had reached minimal levels (<1 cm3/hr) except for the Moreton Bay ash which was still recording 3.057 cm3/hr.

Moreton Bay ash not only recorded the highest sap flow rates (12.854 cm3/hr) but was consistently higher than all Captain Cook trees and black tea tree throughout the day, except between 7-9 am [Figure 2]. Peak flow rates for MCC and black tea trees were the lowest recorded averaging 3.933 and 4.048 cm3/hr respectively. YCC and ACC Cook trees demonstrated intermediate sap flow rates, averaging 7.707 and 7.218 cm3/hr respectively. A similar pattern occurred when sap flow was averaged over all timeframes, months and years [Figure 3]. For example, the sap flow rate of MCC trees was 2 and 4-fold slower than YCC and Moreton Bay ash trees respectively [Figure 3].

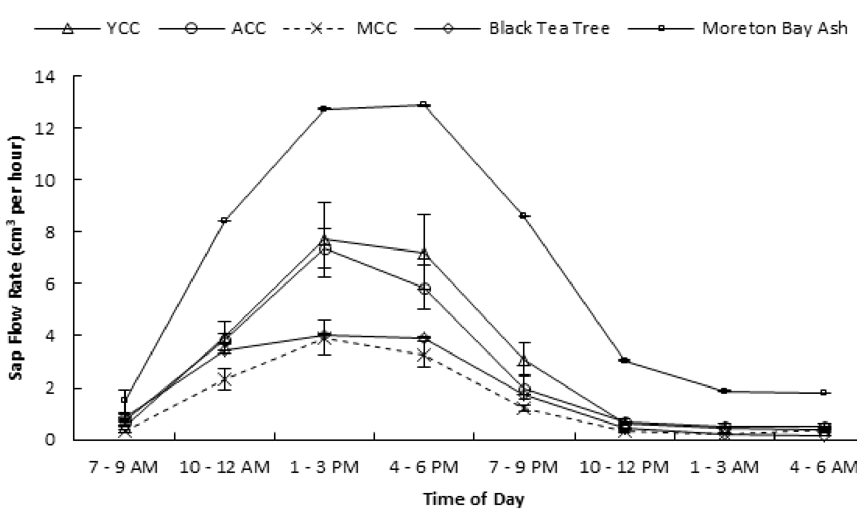

Figure 2: Sap flow rate of young (YCC), adult (ACC) and mature (MCC) Captain Cook trees (CC) and native black tea trees and Moreton Bay Ash as affected by timeframes averaged over all months and years. Vertical bars indicate the s.e. of the means.

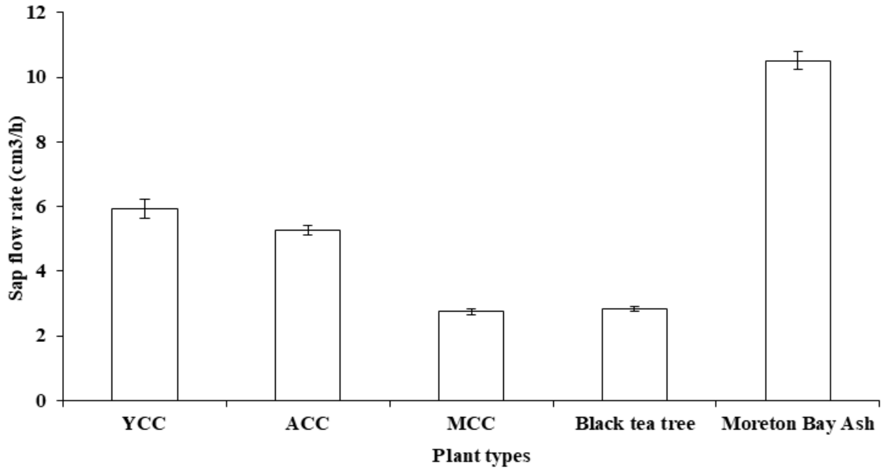

Figure 3: Sap flow rate of young (YCC), adult (ACC) and mature (MCC) Captain Cook trees (CC) and native black tea trees and Moreton Bay Ash averaged over all timeframes, months and years. Vertical bars indicate the s.e. of the means.

Significant differences (P<0.001) in sap flow rate were detected between months, over all timeframes and plant types (Figure 4). Sap flow rates were significantly high during spring (September–November), summer (December–February) and autumn (March–May) compared with winter (June–August). Maximum sap flow rate occurred in January (average of 3.592 cm^3/hr) compared with minimums in June, July and August averaging 2.727 cm^3/hr.

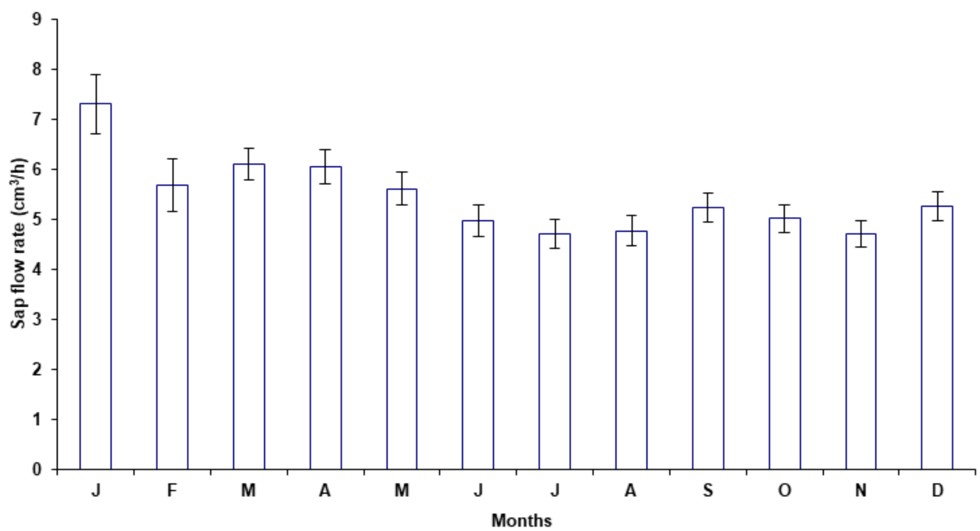

Figure 4: Monthly sap flow rate averaged over all plant types, timeframes and years. Vertical bars indicate the s.e. of the means.

Water use

Significant interactions (P<0.001) in water use occurred between plant types and months [Figure 5 a, b]. For example, significant differences in water use by YCC trees were detected between January and February whereas the same did not occur with ACC and MCC trees and the two native trees. Monthly peak time of water use also varied between plant types with YCC and MCC trees and Black tea trees peaking in January while ACC trees and Moreton Bay ash peaked in March.

The water use magnitude order averaged over all months was Moreton Bay ash>black tea trees>YCC >ACC>MCC trees. Monthly average water use by Moreton Bay ash was 4700 L compared with a minimum of 55 L by MCC trees. The monthly percentage of total volume of water used by Moreton Bay Ash trees, black tea trees, YCC, ACC and MCC trees was 91.8 %, 4.4 %, 1.5 %, 1.3 % and 1.0 % respectively. On average, YCC, ACC and MCC trees used 99% and 72% less water than Moreton Bay ash and black tea trees respectively. MCC trees used the least amount of monthly water compared to its YCC and ACC sisters [Figure 5 b]. Over all plant types and months, high positive correlations were detected between sap flow rate and water volume used (r = 0.93) and between evapotranspiration (P/E factor) and water volume used (r = 0.63).

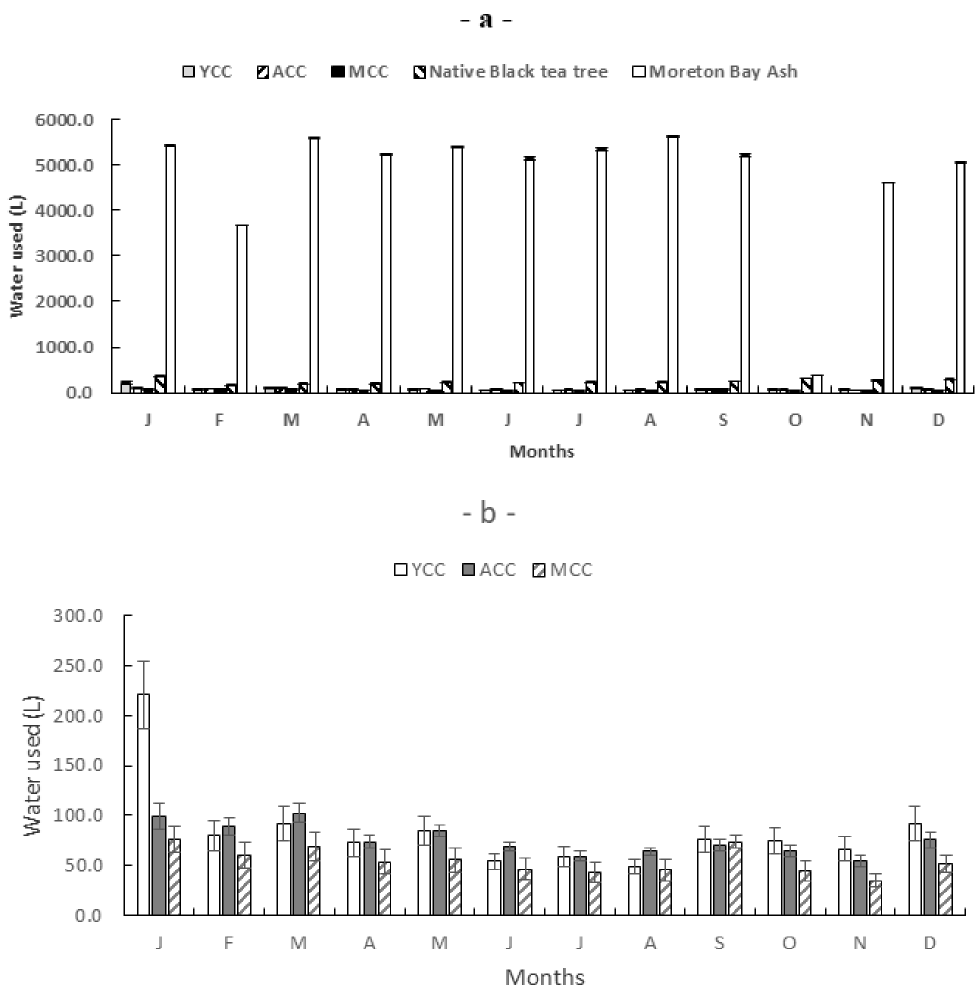

Figure 5: Monthly water used by (a) young (YCC), adult (ACC) and mature (MCC) Capptain Cook trees and native black tea tree and Moreton Bay Ash and (b) young (YCC), adult (ACC) and mature (MCC) Captain Cook trees. Vertical bars indicate the s.e. of the means.

Discussion

This study has provided useful information regarding critical physiological characteristics related to sap flow rates and water use of YCC, ACC and MCC trees compared with black tea tree and Moreton Bay ash, two native trees that coexisted with Captain Cook tree in a riparian area of the dry tropics of northern Queensland. Sap flow rate was faster in YCC compared with MCC trees but was 53% slower than Moreton Bay ash trees. On a daily basis, sap flow rates tended to be highest during early to mid-afternoon for all age groups of Captain Cook tree and the two native trees, although in ACC trees it started to decline slightly from early afternoon. On a monthly basis, sap flow rates were highest over the spring to autumn period (September-May) and lowest during winter (June–August). Average water consumption by Captain Cook trees was 99% and 72% less than Moreton Bay ash and black tea trees respectively. This may be due to differences in size. As for sap flow, over all plant types water consumption was significantly reduced during winter (June–August) compared with spring, summer and autumn.

Wood properties

Sapwood was much deeper in both YCC and ACC trees (100% of the xylem radius) compared with MCC ones (92.9%). Markedly shallower sapwood depth was manifested by Moreton Bay ash (9.4%) and black tea trees (21%) compared with all age groups of Captain Cook tree. These differences are not surprising since sapwood depth (expressed as percent of xylem radius) is related to tree age (Čermák and Nadezhdina 1998) [22]. These internal structural differences may also be attributed to species diversity as well as arbitrary selection of available trees used in this study.

Sap flow rate

The significantly slow sap flow rate across all age groups of Captain Cook trees compared with Moreton Bay ash and black tea trees cannot be explained only in terms of sapwood depth. The relatively deeper depth of Captain Cook's sapwood was expected to produce significantly faster sap flow rates than was reported in this study by comparison with Moreton Bay ash and black tea trees. The inability of Captain Cook trees to exhibit faster sap flow rates compared with the Moreton Bay ash and black tea trees may be attributed to several factors including their innate physiological ability to self-regulate sap flow rate and or regulate loss of water through transpiration more so than Moreton Bay ash and black tea trees, particularly from early night between 7–10 pm until late dawn between 7-9 am as indicated by the slow sap flow rates during these timeframes.

Although the relative depth of sapwood across all age groups of Captain Cook trees was approximately 10- and 5-fold deeper than that of the Moreton Bay ash and black tea trees respectively, the sap flow velocity and water consumption of the Captain Cook trees was significantly lower. This may indicate that Captain Cook trees are relatively more capable of reducing their water flow velocity and water use compared with native trees in the riparian zone. This is not only indicative of a greater adaptation to relatively drier climatic conditions compared with native trees but also indicative of the potential to persist much longer if the climate becomes drier with the advantage of remaining actively reproductive across all seasons of the year (Bebawi et al. 2014, 2015) [23, 24] . Evidence of this claim is indicated by the lower consumption of water in MCC Captain Cook trees compared with the YCC and ACC group. Similar results were reported in stands of maritime pine (*Pinus pinaster* Ait.) where sap flux density was found to be greater in young stands (10 year old) than in 54 year-older stands (Delzon and Loustau 2005) [25]. Differences in sap flow rates between different plant species is common. For example, Moore et al. (2004) found that sap rates in red alder (*Alnus rubra* Bong.) were significantly higher than in Douglas-fir [*Pseudotsuga menziiesii* (Mirb.) Franco] [26].

Water use

The low average consumption of water by Captain Cook trees (72 L month-1) compared with Moreton Bay ash (4719 L month -1) and black tea trees (246 L month-1) may at first glance indicate that they do not significantly affect the supply of water resource. This deduction may be deceptive when considered at the singular plant level rather than at the population level which at 63 00 plant ha-1 may consume 19- and 369-fold more water than Moreton Bay ash and black tea tree, respectively. This deduction is supported by sap flow research on chestnut oak (*Quercus prinus* L.), white oak (*Q. alba* L.), northern red oak (*Q. rubra* L.), black gum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.) and yellow poplar (*Liriodendron tulipifera* L.) which showed that water consumption was largely driven by sapwood area per unit ground area and to a lesser extent by species-specific differences (Wullschleger et al. 2001) [27]. The possibility that changing species composition by that order of magnitude in riparian zones of the dry tropics of Northern Queensland is likely to increase rates of evapo-transpiration and subsequently reduce water yield of stream flow and water table. In Canada, species replacement of hardwood stands by conifers resulted in stream flow reductions (Swank et al. 1988; Hornbeck et al. 1997) [28, 29].

The relatively lower water use consumption observed in this study for black tea trees compared with Moreton Bay ash trees concurs with those reported for similar species along the Daly River in the Northern Territory (O'Grady et al. 2005) [30]. In this instance, it was indicated that the water use was lower in silver paperbark (M. argentea W. Fitzg.) than in ghost gum (*E. papuana* F.Muell.) trees. Also the significantly lower water use by MCC trees compared with YCC trees was also observed in oak trees where maximum SFD (sap flow density) of young cork oak trees (*Q. suber* L.) was greater (3.1 L dm2 h-1) than old cork oak trees (1.2 L dm2 h-1) (Nasr et al 2011). Similarly old trees of an oak stand of *Q. robur* L. also showed lower SFD values than young trees (Vincké et al. 2005) [31, 32].

Management implications

Both economic cost of herbicides and environmental concern about side-effects of herbicides on the environment is of interest to weed control of Captain Cook tree particularly in sensitive riparian areas. Application of herbicides within the context of optimal sap flow rate timeframes across all months reported in this study may lead to both cost and environmental hazard reductions. It is envisaged that herbicide translocation within the plant system may be delivered at a faster rate during optimal sap flow rate timeframes compared with relatively slower sap flow rate timeframes. There is also the possibility that a lower herbicide rate may do the job of killing the weed when applied at peak sap flow rates. These hypothesises can only be verified through future research using results reported in this study. A new outlook to weed management in general may be justified through the extension of the proposed future research.

Furthermore, removal of the high population of Captain Cook trees from the riparian zone is expected in due course to reverse the balance of the natural water resource in favour of native vegetation and restore plant diversity. If Captain Cook populations are removed from the experimental site, it should be done gradually alongside restoration of native vegetation in order not to induce a quick rise of the water table which could bring salt to the surface and stifle efforts of land restoration.

Conclusions

Results from this study indicate that sap flow occurs diurnally and nocturnally across all months in all age groups of Captain Cook tree as well as native Moreton Bay Ash and black tea trees. However, sap flow rate and water consumption of singular Captain Cook trees was considerably slower and lower than native Moreton Bay Ash and black tea trees. They were also slower and lower during winter (June-July) than during other seasons. The early afternoon occurrence of optimal sap flow rate across all age groups of Captain Cook tree is suggestive for optimal timing of some herbicide application techniques and warrants investigation. It is concluded that singular Captain Cook trees are highly conservative in their water consumption compared with native trees but total water consumption is dependent on population density of the weed compared with associate native trees.

In terms of timing control activities, the general consensus for woody weeds such as Captain Cook tree is to apply most treatments when plants are actively growing, although for some weeds several techniques (such as basal barking and cut stump applications) can be effective all year round. This often relates back to the physiology of the plant, which for many rangeland weeds there is a paucity of information to base decisions on. One aspect of particular interest from both a growth and control perspective is in relation to sap flow which may influence the uptake and efficacy of herbicide applications. Stem injection has proven particularly effective for control of Captain Cook tree (McKenzie et al. 2010) and is a treatment that may be affected by the level of sap flow [32]. The present study has provided a basis for future research relevant to timing of herbicide application. It also provides information to better inform the testing of the different application techniques of herbicides including foliar, basal, Hack and Squirt, Cut-stump, Girdle, Stem and Hatchet injection that may be suitable for different times of the year or the day, in direct correlation with the plants sap flow rate.

Conflict of Interest

The authors declare no conflicts of interest.

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