Water use by Eucalypt Clones Growing at Kongowe, Kibaha, Tanzania

[1*]Pima, N.E., [2]Chamshama, S.A.O. and [3]Iddi, S.

[1]Tanzania Forestry Research Institute, P.O. Box 1854,
Morogoro, Tanzania.
[2]Department of Forest Biology, Sokoine University of Agriculture, P.O Box 3010,
Chuo Kikuu. Morogoro, Tanzania.
[3]Department of Wood Utilization, Sokoine University of Agriculture, P.O Box 3014,
Chuo Kikuu. Morogoro, Tanzania.
*Corresponding author, Email: nancypima@yahoo.com

ABSTRACT

A study was carried out between April and October 2014 to investigate the amount of water used by Eucalypt clones grown at Kongowe, Tanzania. Sap flow sensors using heat pulse velocity were deployed across GC 167, GC 15 and GC 940 in wet and dry seasons. Data on water use were analysed using sap flow software. ANOVA was used to compare daily water use between clones and DMRT was used to separate means of daily water use between clones. Correlation was carried out to determine the influence of temperature on water use. Results revealed that GC 167, GC 15 and GC 940 had an average water use of 14, 7 and 5 L day^{-1} respectively in the wet season. During the dry season, water use of 11, 9 and 8 L day^{-1} was recorded for GC167, GC15 and GC940 respectively. Results further showed a strong positive correlation between daily tree water use and temperature. It is concluded that clone GC167 used high amount of water than GC15 and GC940 in the wet season as well as in dry season. It is important to identify where the studied clones should be placed in the landscape to produce the best environmental outcomes.

Keywords: Eucalypt clones, water use, Kongowe, Tanzania

INTRODUCTION

Eucalyptus is the most widely planted tree genus in the world, covering more than 22 million hectares (ha), with growth rates that can exceed 35 $m^3ha^{-1}year^{-1}$ (Nichols *et al.*,2010). These fast growing trees can be grown under a range of different climates for products that include pulp and paper, charcoal, fuel wood and solid wood products such as poles and timber for construction and furniture. They contribute significantly to reducing the wide gap between demand and supply of wood in the shortest possible time (Oballa *et al.* 2009), hence reducing pressure on the few remaining natural forests.

Eucalypt clones were introduced in East African countries of Tanzania, Kenya and Uganda during the period 1997 to 2003 from Mondi South Africa. In Tanzania, clones were introduced in 2003 through Tanzania Forestry Research Institute (TAFORI) to test their adaptability in the Tanzanian environment before large scale planting. Experiments started in 2004 with hybrid clones of *Eucalyptus grandis* x *E. camaldulensis* (GC), *E. grandis* x *E. urophylla* (GU), and *E. grandis* x *E. tereticornis* (GT). These clones combine desired traits for the crossed species. *E. grandis x E. camaldulensis* (GC) combines good growth and drought tolerance, *E. grandis x E. urophylla* (GU) combines good growth and disease resistance while *E. grandis x E. tereticornis*(GT) combines good growth and rooting ability (Cupertino *et al*. 2011).

Eucalypts have been criticised in several countries for consuming excessive amounts of water (KFS 2009, Albaugh *et al.* 2013) and drying out the sub-soil, consequently lowering the water table (Srivastava *et al.* 2003). The worries have persisted up to now in tropical countries such as Ethiopia, Rwanda, Kenya, Tanzania and Uganda (Nduwamungu *et al.* 2007). Observations inCentral India and in the foothill zone of the Himalayas indicate that in regions in which large areas of *E. tereticornis* plantations have been raised, the level of water in wells falls until the plantations are about 6-8 years in age, the culmination of mean annual increment and thereafter reverts to the previous levels (Sunder 1993). In the case of older plantations of *E. globulus* in the Nilgiris (India), no adverse effects have been noticed on the hydrological cycle (Sunder 1993). Although there has been a number of scientific studies undertaken on water use by Eucalypts (Calder 1992, Calder 1999, Lima 2011), variation of species and environments means, generalised conclusions cannot be drawn.

Studies by Dye *et al.* (2004) in Brazil reported mean water use ranging from 30 to 64 L day^{-1} in 1.5 – 7 year old stands of *E. grandis* × *camaldulensis* hybrid clones growing under high soil water availability, good soil type and high temperature and from 15 to 34 L day^{-1} for sites with poor soil condition. Sunder (1993) and Keitel and Adams (2009) reported water use ranging from 20 to 68 L day^{-1}for *E. camaldulensis* and *E. victrix*. Water use by trees is driven by several environmental variables, including vapour pressure deficit, net radiation, wind speed and temperature and also the availability of soil water within the rooting zone (David *et al.* 1997). Morris *et al.* (2004) reported that the rate of water use by Eucalypts is highly variable responding to weather condition, species and hybrid type, soil type and depth, vegetative cover, tree growth stage, wood density and tree rooting depth. Other responses include age and diameter of the trees, leaf area and tree density (Dye *et al.* 1995). The impact of these variables on the amount of water transpired depends on tree leaf area and the stomatal behaviour of the species (White *et al.* 1999).

Studies by Calder *et al.* (1992) in India reported that Eucalypts used more water than crops but less than indigenous forest. The authors further reported that there is no evidence that proves that Eucalypts take more water than any other indigenous dry deciduous and exotic forest. Teshome (2009) in Ethiopia reported that Eucalypts do not consume more water than any tree species and crops; rather they are efficient in using moisture around roots and producing more biomass. However, because of their large size and more abundant leaves with greater leaf area, trees affect stream flow more severely than shorter vegetation when established close to rivers, lakes and estuaries (Lima 2011). High rates of productivity of Eucalypts are often associated with high rates of water use leading to concerns about reductions in yield from water supply catchments in Australia or where Eucalypt forests have replaced native vegetation of low stature in South Africa (Dye, 1996) and southern India (Calder *et al.* 1992). For this reason, nearly all commercial plantation programmes in South America have strict legal limits on how close to a water source they can plant trees (Lima 2011). The severity of problems associated with water availability appears to be greater in areas where the plantations are large in size and cover most of the catchment area or in places with seasonal rainfall. However, lack of adequate data in Tanzanian conditions to justify conclusive decisions on Eucalypts water use is a major constraint to solutions on Eucalypts planting. This study therefore aimed at investigating the amount of water used by Eucalypt clones growing at Kongowe, Kibaha, Tanzania. The information generated from this study will be used as a basis for making decisions on planting Eucalypt clones.

MATERIALS AND METHODS

Study Area Description

This study was conducted at Kongowe, Kibaha, located within Ruvu North Forest Reserve in Pwani Region, approximately 60 km West of Dar es Salaam. The area lies between latitudes 06^{0}42'39''S and longitudes 38^{0}52'52''E. The altitude of the area is 104 m.a.s.l. The area receives bimodal rainfall pattern, with short rains falling between November and December and long rains between March and May. Mean annual rainfall is about 900 mm. Higher temperatures are common in January and February with mean monthly maximum up to 33^{0}C and mean minimum of about 18^{0}C(Msuya *et al.* 2003). The area has sandy soils. The soil pH of the area varies from 4.5 to 4.9 with soil organic carbon ranging from 0.68% to 1.7%. The natural vegetation surrounding the study site is characterized as a semi deciduous open to partly closed woodland with evergreen thickets and riverine forests.

Experimental Design

The experiment was established by TAFORI in 2004 using Eucalypt hybrid clones from Mondi South Africa. Randomized Complete Block Design was used to set up this experiment with four replications and 12 treatments (Eucalypt clones) of which 10 were GCs of *E. grandis x E. camaldulensis*, 1 GT of *E. grandis x E. tereticornis* and 1 GU of *E. grandis x E. urophylla*. Each clone type was represented once in each block (Table 1). Each plot comprised 16 trees spaced at 2.5 x 2.5 m in a 4 x 4 arrangement. The experiment has 2 guard rows planted to avoid edge effect. The experiment was fenced after planting to keep off small game and other intruders. Silvicultural management and previous growth assessments were carried out by TAFORI.

Table 1. Experimental design

Blocks	**Eucalypt clones (Treatments)**											
B4	GC 940	GC 14	**GC** 10	GC 167	GC 581	GC 584	GT 529	GC 796	GU 608	GC 15	GC 785	GC 514
B3	GC 14	GT 529	GC 796	GC 584	GC 15	GU 608	GC 514	GC 785	GC 10	GC 167	GC 940	GC 581
B2	GC 785	GC 15	GU 608	GT 529	GC 581	GC 940	GC 10	GC 14	GC 514	GC 796	GC 584	GC 167
B1	GC 10	GT 529	GC 581	GU 608	GC 514	GC 785	GC 14	GC 167	GC 584	GC 940	GC 796	GC 15

Data Collection

Sap flow measurement

Selection of clones for sap flow measurements were based on their growth performance in terms of survival, Dbh, height, basal area, volume and biomass production. In this case, GC 167, GC 940 and GC 15 were selected for measuring water use in two seasons (wet and dry season). Subjective sampling was applied to select three trees, one tree from each clone type for water use measurements (Cavaleri *et al.* 2014). Data were collected from 30th April and ended on 5th June 2014 in wet season while those for dry season were collected from 13th August and ended on 3rd October 2014. Heat pulse velocity (HPV) was used to estimate whole tree water use for Eucalypt clones. A pulse of heat is injected into the xylem and the velocity of its travel to a point further along the direction of flow is used to estimate sap flow velocity (Simpson 2000). Probes were inserted into holes drilled horizontally into the sapwood at a height of 1.3 m (Dye *et al.* 1996). The probes consisted of two thermistors, one 10 mm upstream and one 5 mm downstream from a heater at the center. The upper and lower thermistors were used to detect the convective and conductive heat fluxes respectively, after a short (0.5-1.5 seconds) heat pulse.Each thermistor contains two temperature sensors, facilitating simultaneous measurement of sap velocity at two different depths in the sapwood (Dye *et al.* 1996). Probes were coated with silicon vacuum grease before insertion to improve thermal contact with the xylem and to aid both installation and removal of needles.

HPV (cm h^{-1}) were collected automatically every 30 minute intervals then averaged over 1 hour for each probe set (Swanson and Whitfield 1981) and stored in an electronic data logger before being downloaded to a computer. Then, sap velocity (V_{si}) was calculated according to the procedures outlined in Swamson and Whitfield (1981). Sapwood area and width were determined by extracting a perpendicular core from each of the sample trees (Table 2).

Table 2. Parameters used for Eucalypt clones water use at Kongowe, Kibaha

Variables measured	**Treatments**		
	GC 167	**GC 15**	**GC 940**
Dhb (cm)	24.5	21	19
Bark thickness (mm)	12	6	6
Sapwood depth (cm)	3.6	2.5	2.7
Sapwood fresh weight (g)	0.271	0.266	0.200
Sapwood dry weight (g)	0.237	0.226	0.182
Sapwood volume (cm^3)	0.481	0.451	0.358
Sapwood area (cm^2)	209.23	135.78	133.17

Sapwood area (A_{sw}) was then calculated using equation 1:

$$A_{sw} = \pi\,(r_{sw}+_{hw})^2 - \pi\,(r_{hw})^2 \quad (1)$$

Where

$r_{sw}+_{hw}$ is the radial thickness of the sapwood plus the heartwood, and $r_{hw}$is the radial thickness of the heartwood (all in cm) (Cavaleri*et al.* 2014).

Therefore, Mean daily water use is calculated using equation 2:

$$\text{Water use (L day}^{-1}) = V_{si} \times A_{sw} \quad (2)$$

Weather data collection

Rainfall and temperature were recorded daily at Kongowe weather station by using rain gauge and glass thermometer respectively. Daily rainfall, minimum and maximum temperatures data were used to plot graphs showing climate trends for two seasons (dry and wet).

Data Analysis

All statistical tests were performed using Sap flow tool software version 1.4 (SFT 2013). ANOVA was used to compare daily water use between clones. DMRT was used to separate means of daily water use between clones. Correlation was carried out to determine the influence of temperature on water use.

RESULTS

Water use

The mean daily water use of studied Eucalypt clones at Kongowe – Kibaha site is shown in Figures 1 and 3. Results revealed that the average water use for GC 167, GC 15 and GC 940 were 14 L day^{-1},7 L day^{-1} and 5 L day^{-1} respectively during wet season (Figure 1). During the measurement period, rainfall totaling 115.9 mm was recorded. During this period, daily minimum and maximum temperatures ranged from 23^0C to 31^0C (Figure 2). Rainfall amounting to 572.2 mm was recorded from 1st April to June 2014 leading to high soil water availability in May and June. During the dry season, clones GC 167, GC 15 and GC 940 consumed an average of 11 L day^{-1}, 9 L day^{-1}, and 8 L day^{-1} respectively (Figure 3). Daily minimum and maximum temperatures recorded ranged from 24^0C to 31^0C (Figure 4) and no rainfall was recorded during the dry season.

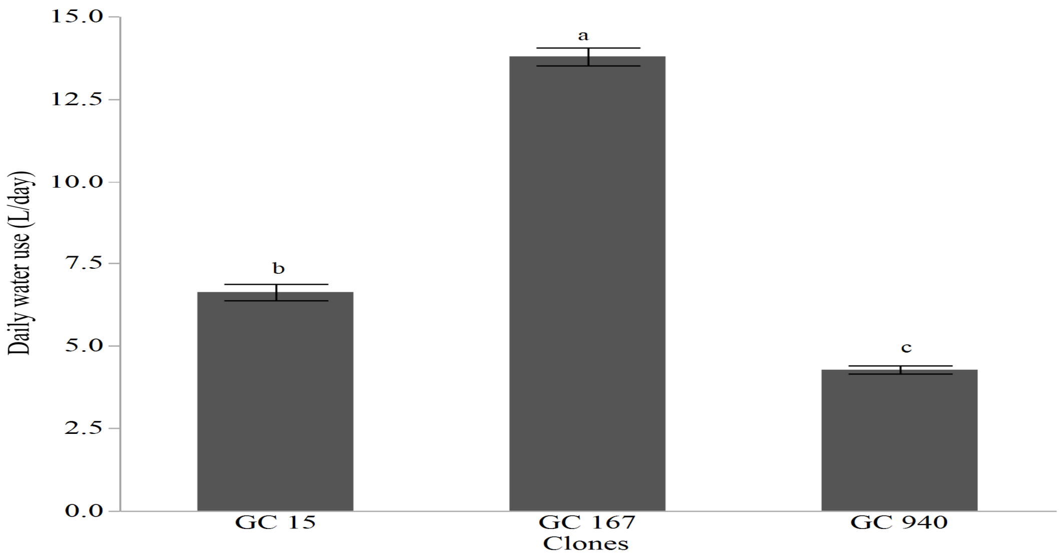

Figure 1: Daily water use of Eucalypt clones in wet season at Kongowe, Kibaha, Tanzania.

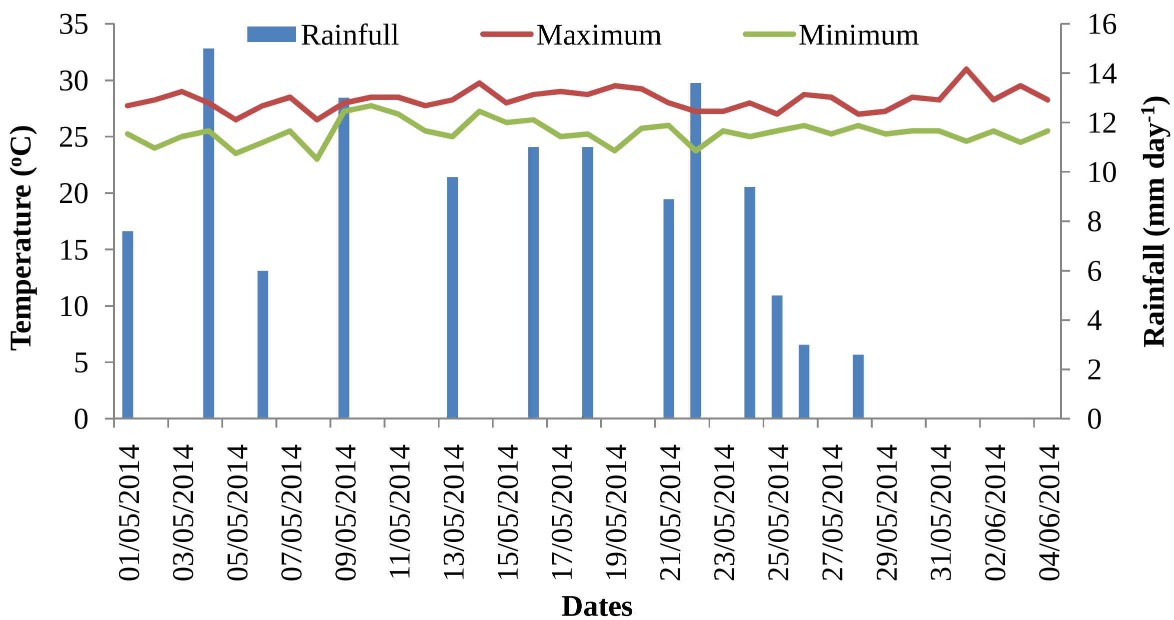

Figure 2: Rainfall and temperature data recorded in wet season at Kongowe, Kibaha, Tanzania.

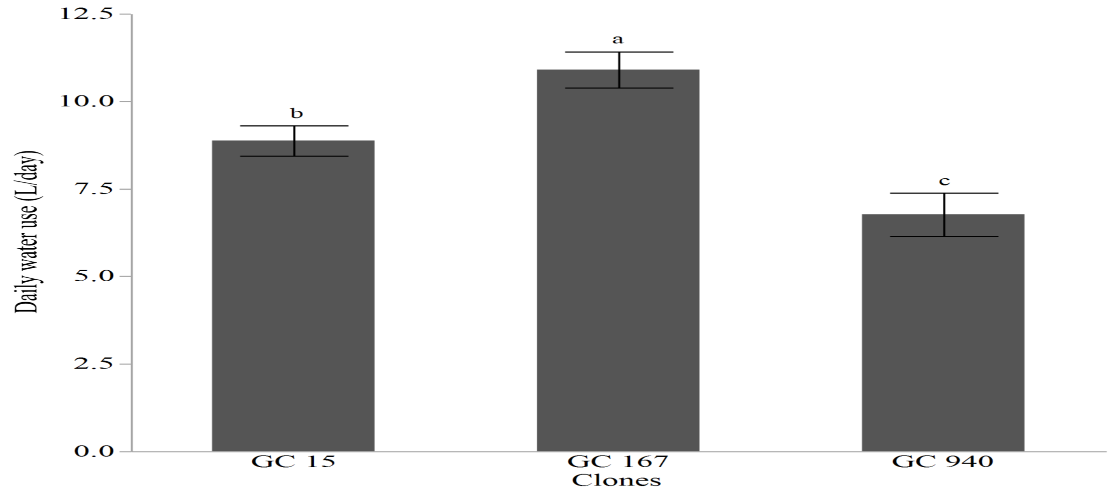

Figure 3: Daily water use of Eucalypt clones in dry season at Kongowe, Kibaha, Tanzania.

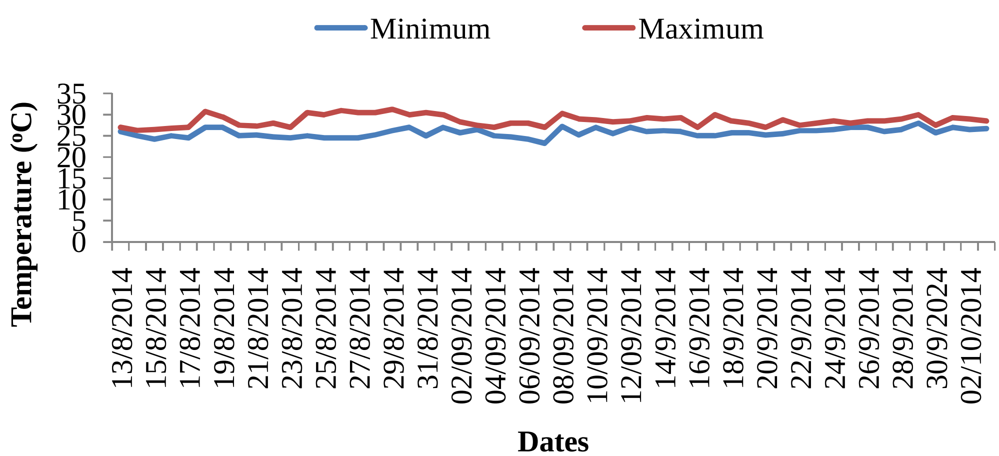

Figure 4: Temperature data recorded in dry season at Kongowe, Kibaha, Tanzania.

Influence of temperature on water use

Temperature had significant ($p<0.05$) correlation with amount of water used by Eucalypt clones (Figure 5). Results revealed that as temperature increased, the amount of water used increased with correction coefficient of 0.34. Figure 6 presents the trends of daily water use of Eucalypt clones in the dry season at Kongowe Kibaha. Results showed that tree water use increased with increasing temperature and soil moisture availability but decreased consistently as the dry season progressed (Figure 6).

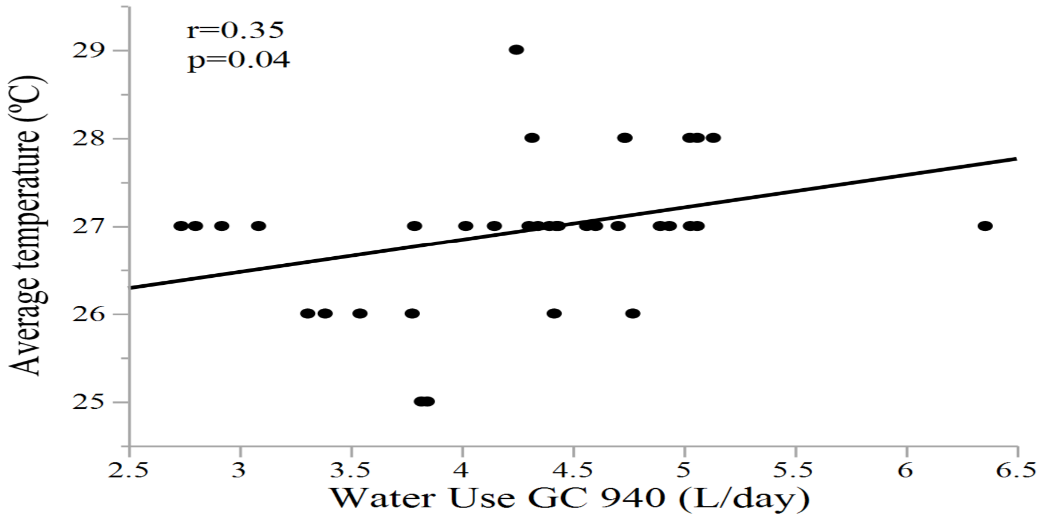

Figure 5: Influence of temperature on water use by Eucalypt clones at Kongowe, Tanzania

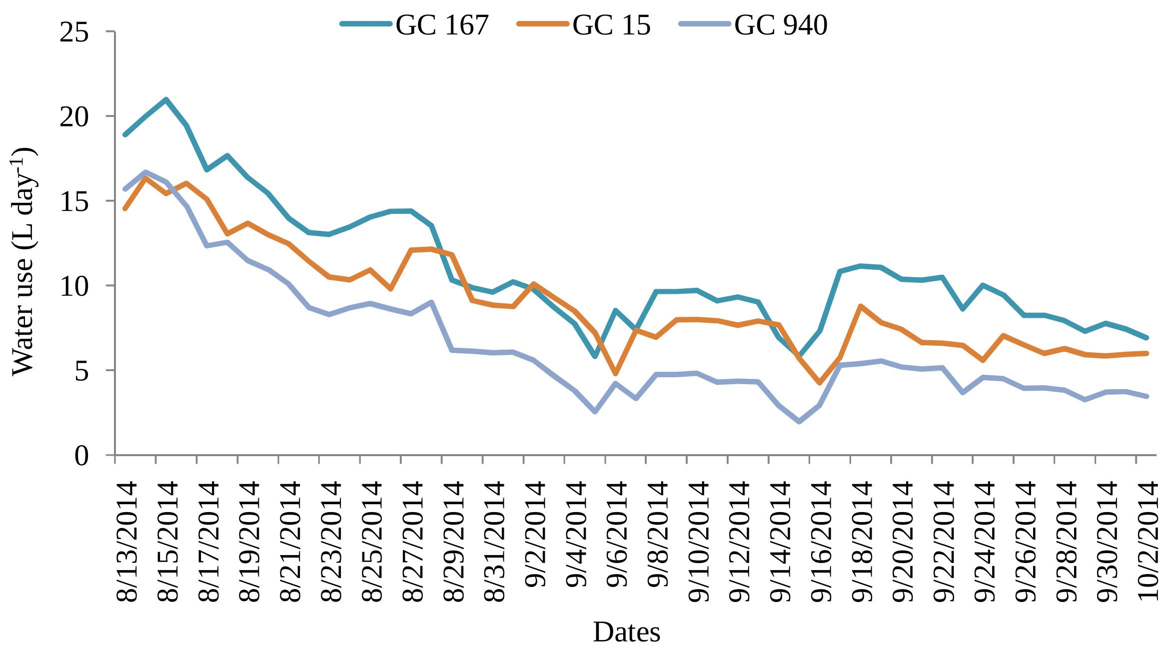

Figure 6: Daily water use trend of Eucalypt clones in dry season at Kongowe, Tanzania

DISCUSSION

GC 167 emerged as the clone with the highest water use in both wet and dry seasons than GC 15 and GC 940 although they were of the same age. This was probably a result of larger diameter ofthe studied tree and the greater sapwood area which transported larger amounts of water. This relationship was also observed in different tropical woody species (Meinzer *et al.* 2004) and a single-species *Acacia mangium* plantation (Cienciala *et al.* 2000). Simpson (2000) and Keitel and Adams

sapwood area and large diameter transported large amount of water than the smallest trees. Alcorn *et al.* (2013) found that smaller sapwood area, crown length and projected crown area of *E. pilularis* resulted in lower water use. A study by Gush (2011) reported that small trees used considerably less water than larger trees of the same species, and this was due to their relatively smaller leaf and sapwood conducting areas. Greater sapwood area would be expected to increase water use by increasing the conductance of the stand as a conduit for water from soil to

In addition, the high rates of water loss from large trees and older forests were likely a result of the influence of an enhanced "pool" of transpirational water in the upper soil layers caused by hydraulic lift (Dawson 1993). The hydraulically lifted water reservoir enabled large trees to use more potential transpirational water during daylight hours than small trees, leading to a greater total water flux. The high variation in water use implies that stem diameters determined the actual quantity of water taken up by trees as the transpiration flux and diameter are normally closely related to conducting wood area (Hatton *et al.* 1995).

Mean water use of Eucalypt clones studied were similar to values reported by Senelwa *et al.* (2009), Alcorn *et al.* (2013) and Fetene (2012) for Eucalypt clones, *E. pilularis*, *E. cloeziana*, *E. globulus*, *Podocarpus falcatus*, *Croton macrostachys* and *Cupressus lusitanica* from Kenya, Australia and Ethiopia. Weltzin *et al.* (2003) and Meinzer *et al.* (2007) reported that the availability of water to trees depends on the amount and timing of precipitation, the ability of the soil to store water and the tree's ability to access resident soil moisture which is dependent on rooting pattern and other root characteristics that affect the efficiency of water uptake. On the other hand, the results were relatively lower than the values reported by Sunder (1993) and Keitel and Adams (2009) ranging from 20 to 68 L day^{-1}for *E. camaldulensis* and *E. victrix* and for other woody tropical species (*e.g.* Meinzer *et al.* 2004; Andrade *et al.* 2005; Kagawa *et al*., 2009). Dye *et al*. (2004) reported mean daily water use in 1.5 – 7 year old stands of *E. grandis* × *E. camaldulensis* hybrid clones ranging from 30 to 64 L day^{-1}for trees growing under high soil water availability, good soil type and high temperature and from 15 to 34 L day^{-1}for sites with poor soil condition. Licata *et al.* (2008) found that an introduced pine species (*Pinus ponderosa*) in Argentina used significantly more water than native cypress species (*Austrocedrus chilensis*). Vance *et al.* (2014) reported that Eucalypts' water use can be higher than non-irrigated agricultural crops, pasture and in some cases, native forests due to their rapid growth and high evapotranspiration rates.

Several factors might be contributing to low water use of studied clones compared to the values reported by Sunder (1993), Dye *et al.* (2004) and Keitel and Adams (2009). This could probably be a result of genetic differences and the environmental interaction as supported by Dye and Olbrich (1993). David *et al.* (1997) and Morris *et al.* (2004) reported that the rate of water use by Eucalypts is highly variable responding to weather conditions, species and hybrid type, soil type and depth, vegetative cover, tree growth stage, wood density and tree rooting depth. Others factors include soil water availability, age and diameter of the trees, leaf area and tree density.Morris *et al.* (2006) compared single species of *E. camaldulensis* on two sites with contrasting conditions in Australia and Pakistan and found about 3 times more water use by *E. camaldulensis* in Pakistan environments compared to that in Australia. Changes in water use are determined primarily by changes in climatic demand or by physiological responses to an increase in soil water availability or both (Calder 1992).

Results showed a strong positive correlation between daily tree water use and temperature. This relationship was also observed for other *Eucalyptus* species in Pakistan and Australia (Morris *et al.* 2006). The authors compared single species of *E. camaldulensis* on two sites in Australia and Pakistan. The Australia site was established in low temperature zone while the Pakistan site was established in high temperature zone. The authors found about 3 times more water use by *E. camaldulensis* in Pakistan environments compared to that in Australia. Calder (1992) reported that changes in water use are determined primarily by changes in climatic demand or by physiological responses to an increase in soil water availability or both. Gush (2011) concluded that seasonal variations in sap velocity are highly correlated to climatic stimuli such as changes in temperature and day length.

Tree water use increased with increasing temperature and soil moisture availability but decreased consistently as the dry season progressed. The decreasing trend in water use observed was probably a result of decreasing soil moisture around the rooting zone. Low soil moisture decreased transpiration as the leaf stomata closes to reduce the rate of water loss, such that the trees transpired more during the wet season than during the dry season (Knight 1999). Early closure of stomata as soil dries conserves soil water and could be advantageous if drought is prolonged (Sinclair and Muchow 2001). Stomata closure, either in response to increasing vapour pressure deficit or soil water deficit is one of the mechanisms trees use to avoid drought conditions (Schulze 1986, Dye *et al.* 2001). Closure of stomata to maintain leaf water potential above a critical threshold protects the xylem from damage by cavitation and embolism (Tyree and Sperry 1988).Baldocchi and Xu (2007) reported that under seasonal rainfall conditions with extended drought periods, trees have to cope with water shortage and they have developed strategies to adjust at structural, physiological and chemical levels.

A decline in water use with soil drying is a commonly observed phenomenon in trees including *E. globulus*, *Podocarpus henkeli* and *Pinus radiata*. David *et al.* (1997) found that water use of an *E. globulus* stand in Portugal decreased consistently as the dry season progressed. Gush *et al.* (2011) found water use for *Podocarpus henkeli* and *Pinus radiata* ranging between 10 and 20 L day^{-1} and 50 – 100 L day^{-1} during the summer, declining marginally to between 5 and 15 L day^{-1} and 30 L day^{-1} respectively in winter. In addition, *Tectona grandis* used less water during the dry season than during the wet season, which can be explained by the reduced number of leaves during the dry season (Kunert 2010). In contrast, trees with the ability to take up soil water from deeper layers maintained or even increased rates of water use during dry periods (Meinzer *et al.* 1999, Knight 1999). For example, semi-deciduous species *Anacardium excelsum,* fully foliated during the dry season, had significantly higher water use rates during the dry season, possibly caused by a higher evaporative demand and due to the use of groundwater (Kunert 2010). According to Dye and Olbrich (1993), normal water use rates may decline during times of significant soil water deficit.

CONCLUSION

The results indicated that Eucalypt clones studied used much less amount of water than other *Eucalyptus* species and other tree species reported elsewhere. GC 167 showed high water use than GC 15 and GC 940 in both seasons and reduced its water use during dry season, displaying a better control of its water use. Results further showed a strong positive correlation between daily tree water use and temperature of the study area. It is recommended that it is important to identify where the studied clones should be placed in the landscape to produce the best environmental outcomes. Further studies on water use efficiency of the studied Eucalypt clones need to be carried out. In this study, water use efficiency was not carried out due to time limitation. In order to assess water use efficiency, monitoring for water use and biomass production needs to be carried out for at least a year. This information will help to decide where these clones should be planted on the landscape to produce better outcomes.

ACKNOWLEDGEMENT

The authors thank the Commission for Science and Technology (COSTECH) for financing PhD of the first author and TaFF for financial support to purchase equipments used in water use measurements. The authors are also grateful to Tanzania

Forestry Research Institute (TAFORI) for permitting use of trials.

REFERENCES

Albaugh, J.M., Dye, P.J. and King, J.S. 2013. Eucalyptus and Water Use in South Africa. Review Article. International Journal of Forestry Research 2013: 1 – 11.

Alcorn, P.J., Forrester, D.I., Thomas, D.S., James, R., Smith, R.G.B., Nicotra, A.B. and Bauhus, J., 2013. Changes in Whole-Tree Water Use Following Live-Crown Pruning in Young Plantation-Grown *Eucalyptus pilularis* and *Eucalyptus cloeziana.*Forests4: 106 – 121.

Andrade, J.L., Meinzer, F.C., Goldstein, G. and Schnitzer, S.A. 2005. Water uptake and transport in lianas and co-occurring trees of a seasonally dry tropical forest. Trees – Structure and Function19: 282–289.

Baldocchi, D.D. and Xu, L. 2007. What limits evaporation from Mediterranean oak woodlands – The supply of moisture in the soil, physiological control by plants or the demand by atmosphere? Advances in Water Resources 30: 2113 – 2122.

Calder, I.R. 1992. Water use of eucalypts - a review. In: Growth and Water Use of Forest Plantations. (Edited by Calder, I. R., Hall, R. L., Adlard, P. G,), John Wiley and Sons Publisher, New York. pp 167–179.

Calder, I.R., Swaminath, M.H., Kariyappa, G.S., Srinivasalu, N.V., Srinivasa, M.K.V. and Mumtaz, J. 1992. Deuterium tracing for estimation of transpiration from trees. Measuements of transpiration from *Eucalyptus* plantation, India. *Journal of Hydrology* 130: 37 – 48.

Calder, I.R. 1999. The Blue Revolution: Land Use and Integrated Water Resources Management. Earthscan Publications, London. 192p.

Cavaleri, M.A., Ostertag, R., Cordell, S. and Sack, L. 2014. Native trees show conservative water use relative to invasive trees: results from a removal experiment in a Hawaiian wet forest. Conservation Physiology 2: 1093 – 1104.

Cienciala, E., Kucera, J. and Malmer, A. 2000. Tree sap flow and stand transpiration of two*Acacia mangium* plantations in Sabah, Borneo. Journal of Hydrology 236: 109-120.

Cupertino, F.B., Leal, J.B., Corrèa R.X. and Gaiotto F.A. 2011. Genetic diversity of *Eucalyptus* hybrids estimated by genomic and EST microsatellite markers. Bio Plantarum55(2): 379-382.

David, T.S., Ferreira, M.I., David, J.S. and Pereira, J.S. 1997. Transpiration from a mature *Eucalyptus globulus* plantation in Portugal during a spring–summer period of progressively higher water deficit. Oecologia 110: 153–159.

Dawson, T.E. 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. Oecologia 95:565–574.

Dye, P.J. and Olbrich, B.W. 1993. Estimating transpiration from 6-year-old Eucalyptus grandis trees: development of a canopy conductance model and comparison with independent sap flux measurements. Plant Cell and Environment 16: 45 – 53.

Dye, P.J., Olbrich, B.W. and Everson, C.S. 1995. The water use of plantation forests and montane grassland in summer-rainfall forestry regions of South Africa. *Proceedings of the Seventh South African National Hydrological Symposium*. 4 – 6 September 1995, Institute of Water Research, Grahamstown. 28 – 42pp.

Dye, P.J., Soko, S. and Poulter, A.G. 1996. Evaluation of the heat pulse velocity method for measuring sap flow in *Pinus patula.*Journal of Experimental Botany47(300): 975 – 981.

Dye, P.J. 1996. Climate, forest and stream flow relationships in South African afforested catchments. Community Forest Review 75: 31 – 38.

Dye, P., Vilakazi, P. Gush, M., Ndlela, R. and Royappen, M. 2001. Investigation of the feasibility of using trunk growth increments to estimate water use of *Eucalyptus grandis* and *Pinus patula* plantations. Tree Physiology16: 233 – 238.

Dye, P.J., Jacobs, S. and Drew, D. 2004. "Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* Plantation stands in Zululand, South Africa." Forest Ecology and Management 193(2): 197 – 218.

Fetene, M. 2012. Studies in tree hydrology: Strategies of water use in co-occurring exotic and indigenous species, Munessa Forest. Addis Ababa, Ethiopia. 43p.

Gush, M.B. 2011. Water-use, growth and water-use efficiency of indigenous tree species in a range of forest and woodland systems in South Africa. Thesis for Award of PhD Degree at University of Cape Town, South Africa, 184pp.

Gush, M.B., Dye, P.J., Geldenhuys, C.J. and Bulcock, H.H. 2011. Volumes and efficiencies of water-use within selected indigenous and introduced tree species in South Africa: Current results and potential applications. *Proceedings of the 5th Natural Forests and Woodlands Symposium,* 11-14 April 2011, Richards Bay. pp 1 – 13.

Hatton, T.J., Moore S.J. and Reece, P.H. 1995. Estimating stand transpiration in a *Eucalyptus populnea* woodland with the heat pulse method: Measurement errors and sampling strategies. Tree Physiology 15:219–227.

Kagawa, A., Sack, L., Duarte, K. and James, S.A. 2009. Hawaiian native forest conserves water relative to timber plantation: Species and stand traits influence water use. Ecological Applications19: 1429–1443.

Keitel, C. and Adams, M.A. 2009. Climate, Management and Ecosystem Interactions in the Pilbara. Tree Water Use at Millstream National Park, Sydney. 30p.

KFS. 2009. Kenya Forest Services, A guide to on-farm Eucalyptus growing in Kenya. Kenya Forest Services, Ministry of Forestry and Wildlife, Kenya. 29p.

Knight, J.H. 1999. "Root distributions and water uptake patterns in eucalypts and other species," in *The Ways Trees Use Water* (Edited by Landsberg, J), Water and Salinity Issues in Agroforestry No. 5, RIRDI, Barton, Australia. pp. 66–102.

Kunert, N. 2010. Tree transpiration in Forest Plantations: Effects of species, seasonality and diversity (Panama). Dissertation for the Degree of Doctor of Philosophy in Forestry University of Göttingen. 106pp.

Licata, J.A., Gyenge, J.E., Fernández, M.E., Schlichter, T.M. and Bond, B.J. 2008. Increasedwater use by ponderosa pine plantations in northwestern Patagonia, Argentina compared with native forest vegetation. Forest Ecology and Management255: 753–764.

Lima, W.P. 2011. Plantation Forestry and Water: Science, Dogmas, Challenges. Instituto Bioatlântica, Rio de Janeiro, Brazil. 65p.

Meinzer, F.C., Andrade, J.L., Goldstein, G., Holbrook, N.M., Cavelier, J. and Wright, S.J. 1999. Partitioning of soil water among canopy trees in a seasonally dry tropical forest. Oecologia 21: 293 – 301.

Meinzer, F.C., James, S.A. and Goldstein, G. 2004. Dynamics of transpiration, sap flow and use of stored water in tropical forest canopy trees. Tree Physiology24: 901–909.

Meinzer, F.C., Warren, D.R. and Brooks, J.R. 2007. Species-specific partitioning of soil water resources in an old-growth Douglas-fir-western hemlock forest. Tree Physiology 27: 871–880.

Morris, J., Ningnan, Z., Zengjiang, Y., Collopy, J. and Daping, X. 2004. Water use by fast-growing *Eucalyptus urophylla* plantations in southern China. Tree Physiology 24: 1035–1044.

Morris, J., Collopy, J. and Mahmood, K. 2006. Canopy conductance and water used *Eucalyptus* plantations. Pakistan Journal of Botany 38(5): 1485-1490.

Msuya, T.S., Shilogile, E., Mndolwa, M.A. and Sabas, E. 2003. Potentials of joint forest management embracing agroforestry in improving the livelihoods of communities adjacent to forest area: observations from Ruvu Fuel wood Pilot Project, Tanzania. TAFORI Newsletter3(2): 32–39.

Nduwamungu, J., Munyanziza, E., Nduwamungu, J.D., Ntirugulirwa B., Gapusi, R.J., Bambe, J.C., Ntabana, D. and Ndizeye G. 2007. Eucalyptus in Rwanda: Are the Blames True or False?Institute Des Sciences Agronomiques Du, Rwanda. [stud.epsilon.slu.se/4297/1 /Otuba_M_ 2012.pdf].

Nichols, J.D., Smith, R. G. B., Grant, J. C. and Glencross, K. 2010. Subtropical eucalypt plantations in Eastern Australia. Journal of Australian Forest 73: 53 – 62.

Oballa, P.O. Konuche, P.K.A. Muchiri M.N. and Kigomo, B.N. 2009. *Facts on Growing and Use of Eucalyptus in Kenya*. Kenya Forestry Research Institute, Nairobi, Kenya. 37pp.

Schulze, E.D. 1986. “Carbon dioxide and water vapor exchange in response to drought in the atmosphere and in the soil,” Annual Review of Plant Physiology 37: 247–274.

Senelwa, K., Etiegni, L., Kirongo, B.B., Ototo G.O., Imo, M. and Ogweno, D. 2009.Misunderstandings of the Impacts of Planting Eucalyptus Species in Kenya: Criticisms and Misconceptions. [www.kenyaforestservice.org/Eucalyptus%guidelines%20%Final].

SFT 2013. Sap flow tool. Analysis and visualization of sap flow data. [http://www.sapflowtool. com /SapFlowToolManual.htm].

Simpson, D.G. 2000. Water use of interior Douglas-fir. *Canadian Journal of Forestry Research* 30: 534 – 547.

Sinclair, T.R. and Muchow, R.C. 2001. System analysis of plant traits to increase grain yield on limited water supplies. Journal of Agronomy 93: 263–270.

Srivastava, R. J., Kumar, A. and Prasad, K. 2003. Studies on Soil Moisture Variations under *Eucalyptus* Plantation.Rome: FAO. [http://www.fao.org/docrep/article/wfc/x11/B2.htm].

Sunder, S.S. 1993.The ecological, economic and social effects of eucalyptus. Proceedings of the Regional expert consultation on Eucalyptus. [http://www.fao.org/docrep/05/htm#TopPg].

Swanson, R.H. and Whitfield, D.A.W. 1981. A numerical analysis of heat pulse velocity theory. Journal of Experimental Botany32: 221 – 239.

Teshome, T. 2009. Is Eucalyptus ecologically hazardous tree species? Ethiopia. *Journal for* Research and Innovation Foresight1(1): 128 – 134.

Tyree, M.T. and Sperry, J.S. 1988. “Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress?” Plant Physiology 88: 575–580.

Vance, E.D., Loehle, C., Wigley, T.B. and Weatherford, P. 2014. Scientific Basis for Sustainable Management of *Eucalyptus* and *Populus* as Short-Rotation Woody Crops in the U.S.Forests5: 901 – 918.

Weltzin, J.F., Loik, M.E. and Schwinning, S. 2003. Assessing the response of terrestrial ecosystems to potential changes in precipitation. BioScience53:941–952.

White, D.A., Beadle, C.L. and Worledge, D. 1999. Control of transpiration in an irrigated *Eucalyptus globulus*Labill. Plantation Plant Cell and Environment 23: 123–134.