MODELING CROP WATER STRESS INDEX (CWSI) IN TREE SEEDLINGS

By

SNEHA, C.
(2009-17-101)

THESIS

Submitted in partial fulfilment of the

requirement for the degree of

Master of Science in Forestry

Faculty of Forestry

Kerala Agricultural University

DEPARTMENT OF TREE PHYSIOLOGY AND BREEDING
COLLEGE OF FORESTRY
VELLANIKKARA, THRISSUR-680 656
KERALA, INDIA

2011

DECLARATION

I, Sneha, C. (2009-17-101) hereby declare that the thesis entitled **"Modeling crop water stress index (CWSI) in tree seedlings"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other University or Society.

Vellanikkara **Sneha, C.**

16/08/2011 **2009-17-101**

Dr . A.V. Santhoshkumar
Associate professor and Head
Dept.of Tree Physiology and Breeding,
College of Forestry,
Kerala Agricultural University,
Vellanikkara, Thrissur-680 656

Dated: 16/08/2011

CERTIFICATE

Certified that this thesis, entititled "**Modeling crop water stress index (CWSI) in tree seedlings**" is a record of research work done independently by **Miss.Sneha,C**. **(2009-17-101)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Dr.A.V.Santhoshkumar
Chairman
Advisory committee

CERTIFICATE

We, the undersigned members of the Advisory Committee of **Miss.Sneha,C**. **(2009-17-101)** a candidate for the degree of **Master of Science in Forestry**, agree that the thesis entitled "**Modeling crop water stress index (CWSI) in tree seedlings**" may be submitted by **Miss. Sneha,C**. **(2009-17-101)** in partial fulfilment of the requirement for the degree**.**

Dr . A.V. Santhoshkumar
Associate professor and Head
Dept.of Tree Physiology and Breeding,
College of Forestry,
Vellanikkara, Thrissur
(Chairman)

Dr. P. K. Ashokan
Professor
Dept. of Tree Physiology and Breeding,
College of Forestry,
Vellanikkara, Thrissur
(Member)

Dr. K. Nandini
Professor and Head,
Dept. of Plant Physiology,
College of Horticulture,
Vellanikkara**,** Thrissur
(Member)

Dr. K.M. Sunil
Assistant Professor,
Agricultural Meteorology,
RARS, Ambalavayal
Kerala Agricultural University,
Vellanikkara, Thrissur
(Member)

Acknowledgement

*I express my deepest sense of respect, gratitude and indebtedness to **Dr. A.V Santhoshkumar**, Associate Professor & Head, Department of Tree physiology and Breeding, College of Forestry, Kerala Agricultural University and Chairperson of my advisory committee for his meticulous guidance, constant encouragement, ever willing help, constructive criticism, continuous support, creative ideas, well timed advice, painstaking scrutiny of the manuscript, extreme patience, motherly affection, good understanding, guiding spirit. Gifted I am, to relish a few from his ocean of knowledge, experience, perseverance and perfection. I consider myself fortunate in having the privilege of being guided by him.*

*I wish to place on record my sincere gratitude with due respect and whole hearted thankfulness to **Dr. P.K Ashokan**, Professor, and Department of Tree physiology, College of Forestry, Vellanikkara, for his scholarly suggestions, critical scrutiny of the manuscript and unbound support rendered throughout my investigation.*

*I am very much obliged to **Dr. K, Nandini**, Professor & Head, Department of Plant physiology, College of Horticulture, Vellanikkara, for her eminent suggestions, critical assessment and Priceless support, invigorating discussions throughout my study, without which the preparation of this thesis would have been easier said than done.*

*I extent my profound sense of gratitude to **Dr. K.M Sunil**, Assistant Professor, RARS, Ambalavayal for his unwavering encouragement, unflagging perseverance, well timed support and help rendered which made the successful completion of this thesis possible.*

*I wish to express my sense of gratitude to **Dr. B.Mohankumar**, Associate Dean, College of Forestry, **Dr. K, Vidyasagar, Mr. S. Gopakumar, Dr. P.O.Nameer, Dr. T.K, Kunhamu, Dr. E.V. Anoop** and **Dr. N.Vijayakumar** of College of Forestry for their help and support during my study.*

*I express heartfelt thanks to teaching and non teaching staffs of Department Tree physiology and Breeding for their timely suggestions and encouragements provided throughout the course of my study. Special mention goes to **Mr.Srinivasan**; Teaching Assistant **Mr. Prasanth,** and **Mrs. Soumya.** The help rendered to me by **Mrs. Padmavathy** and **Mrs. Jyothy** is also remembered with gratitude.*

I am grateful to all nursery workers for their ever willing help, great support and kind co-operation rendered throughout my work. My special thanks to ***Mrs. Prema, Mrs. Rema, Mr. Prasad and Mr. Madhu*** *for their patience in helping me during nursery work.*

I thankfully acknowledge the co- operation and help rendered by my seniors ***Kum.Deepa, K.S, Kum.Neenu Somaraj, Kum. Neethulakshmi, Mr.Ajaygosh, Mr.Malik Fasil*** *and all my juniors.*

I duly acknowledgement the full heart, personal sacrifices, incessant encouragement, moral support and timely persuasions by my friends ***Mr. Shiran, Kum. Sukanya****,* ***Mr. Aneesh*** *and* ***Mrs. Shiny Gopakumar*** *not only in my research but also throughout my career.*

Let me place on record my heartiest thanks to ***Delphy, Sindhumathy, Dhanya, Keerthy, Sreehari, Sreejith, Shine, Aneesh, Aisha, Shabina and Swathy*** *for their friendly help during the course of my work.*

I am thankful to my juniors ***Parvathy, Soorya, Meera, Nijin, Ajeesh, Anoob, Anand, Freddy, Kiran and all others*** *for their sincere help, support and encouragement.*

I am in dearth of words to express my gratitude and indebtedness to my roommates ***Renisha, Nimmy, Ankita , Susha*** *and* ***Jyothi*** *for their boundless affection, personal sacrifices, constant prayers and unceasing encouragement in my entire Endeavour.*

I express my deep sense of gratitude to ***Kerala Agricultural University*** *for extending financial and technical support for pursuance of my study and research.*

At this juncture, I express my deep love to my ***parents, sister, brothers*** *and* ***all my family members*** *without whose moral support, blessings and affection this would not have been a success.*

A word of apology to those I have not mentioned in person and notes of thanks to one and all that worked for the successful completion of the Endeavour.

*Above all I bow my head before GOD '****ALMIGHTY****' without whose blessings enabled me to undertake this venture successfully.*

Sneha. C

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

INTRODUCTION

Water is one of the most important natural resources and a major part of available water is used for irrigation. Presently, almost 60 per cent of global fresh water usage is for irrigation purposes (USGS, 2006) and the available water is decreasing constantly due to its excessive consumption. In the nursery, water management and irrigation costs around 50 per cent of total costs involved. Still drought or water stress limits plant growth and field crops production more than any other environmental stresses (Zhu, 2002). With the increasing demand for tree seedlings for planting and afforestation purpose, the number of forest nurseries are increasing and so is the water requirement for irrigation. A better understanding about the effect of abiotic stress and plant responses will help nursery managers and foresters to avoid large scale failures in different planting programmes (Rao, 2005).

Productivity response to water stress is different for each crop and is expected to vary with the climate. Many factors need to be accounted for in order to obtain a good measure of actual stress levels, among which leaf temperature is the most important factor (Stockle and Dugas, 1992) and has been effectively used for irrigation scheduling. Critical values of the crop water stress index (CWSI) are determined for a particular crop in different climates and soils for use in irrigation management. The use of canopy temperature to detect water stress in plants is based upon the assumption that transpired water evaporates and cools the leaf surface below the temperature of the surrounding air. As water becomes limiting, transpiration is reduced and the leaf temperature increases. If little water is transpired, leaves will warm above air temperature because of absorbed radiation. Therefore the canopy to air temperature difference gives an ideal representation of crop water stress levels. Infrared thermometers provide a good means for determination of canopy temperature.

In India, teak and mahogany are two commercially important timber species that are widely used for raising plantations and afforestation purposes. Both species require a relatively long nursery period lasting about one year. However, these two species are still poorly studied in relation to its management in plantations and its physiological responses to environmental stresses. Standardization of nursery techniques is necessary in any afforestation programme as expenditure on nursery takes itself a major portion of plantation cost. The cost can however, be reduced by evolving suitable and desired nursery practices on scientific lines (Bahuguna and Lal, 1992). Determination of optimal watering frequency and water requirement for teak and mahogany seedlings is very essential. Hence the present study is oriented to explore the use of CWSI to predict water stress in tree seedlings to provide a method for early detection of water stress.

The present study has been formulated with the following objectives:

1. To detect water stress in seedlings of *Tectona grandis* and *Swietenia macrophylla* with the help of infrared thermometry by developing a crop water stress index (CWSI).
2. To compare the effect of different stress levels in physiological and biometric characteristics of seedlings.
3. To compare the effect of water stress in teak and mahogany.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Water comprises 70 to 85 per cent of the fresh weight of most of the plants. It is a means of transportation for food materials and the medium in which these products move from one plant part to another. Water acts as a solvent for mineral nutrients and the complex substances synthesised within the plant. It maintains cell turgidity and helps in cell elongation and cell division. Evapotranspiration helps the plant to control its surface temperature and provides refrigeration for the plant. Plants continuously absorb and lose water. Los of water from plants is mainly through the process of evapotranspiration.

It has been estimated that a leaf will exchange up to 100 per cent of its water in a single hour on a warm, dry, sunny day and an amount equivalent to 100 times of its fresh weight during the whole lifetime (Taiz and Zeiger, 2006). Plant water stress occurs when the amount of water transpired is greater than the amount the roots can absorb (McDonald 1984; Aber and Melillo 1991). Transpiration can exceed absorption in several circumstances. Root absorption can be reduced by limited soil water, cold soils, and soils that have a high salt concentration. Transpiration can be increased by high temperatures, low humidity, and windy conditions (Raven et al., 1986). Plant water deficit can impair cell division, plant growth, photosynthesis, respiration, and other physiological processes (Kozlowski et al., 1991). Periods of soil and/or atmospheric water deficit often occur during a plant's life cycle even outside the arid/semi-arid regions, as reported for temperate deciduous forests (Law et al., 2000; Wilson et al., 2001) or tropical rainforests (Grace, 1999). In the latter, for example, water limitation may prove to be a critical constraint to primary productivity under future scenarios of more arid climates due to global climate change (Fischer et al., 2001).

2.1. Crop water stress index (CWSI)

Plants keep their temperature a few degrees lesser than that of atmosphere.

was first reported by Rameaux in 1843. This was observed further by Miller and Saunders (1923); Eaton and Belden (1929). Leaf temperature was found to be 7^0C less than the air temperature (Wallace and Clum, 1938). The reason for this decrease was explained as erroneous air temperature measurements, radioactive cooling and other factors (Curtis, 1936; Curtis et al., 1938). However, leaf temperature was found to be highly influenced by environmental and other plant factors thus makes its interpretation extremely difficult (Idso et al., 1966). Later on Ehrler (1973) conclusively demonstrated that leaf temperatures could be cooler than the air temperature and is a function of the vapour pressure deficit of the air.

With the advancement of use of infrared technology, crop canopy temperature was effectively measured to quantify plant water stress. Monteith and Szeicz (1962) and Tanner (1963) were the first to use infrared thermometry to measure plant temperature and quantify plant water stress. Fuchs and Tanner (1966) proposed the first basic technique to employ IRT (infrared thermometer) determined crop temperature to assess the severity of water deficit. Since then multiple indices have been proposed and used to quantify plant water stress. Idso et al. (1977) used canopy temperature (T_c) and the air temperature (T_a) to create the stress-degree-day (SDD) index of crop water status and related it to yield and plant water requirements. SDD merely related canopy temperature measured by an infrared thermometer, to air temperature, suggesting that if (T_c – T_a) were negative, the plants were well watered, but that if the differential was positive, water was needed by the plant. This simple approach proved adequate in many subsequent studies (Ehrler et al., 1978; Idso et al., 1978, 1979, 1980; Reginato et al., 1978; Walker and Hatfield, 1979) especially in arid areas. But many experiments indicated that the foliage air temperature differential alone was not sufficient to handle complexities introduced by significant microclimatic variations of either a temporal or spatial nature (Gardner, 1979; Walker, 1980). Later on, Idso et al. (1981) and Jackson et al. (1981) exploited the relation between plant air temperature difference and vapour pressure deficit of the air to develop CWSI.

The theoretical explanation for CWSI was based on the energy balance equations. Based primarily on plant foliage temperatures, this index has been shown to be closely correlated with soil moisture content, soil water matrix potential, soil salinity, soil water logging, plant water potential, leaf diffusion resistance, photosynthesis, as well as final crop yield (Idso et al., 1981; Idso, 1982). CWSI can be calculated as follows according to Idso et al. (1981)

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}}$$

where T_c is the canopy temperature, T_a the air temperature, *ll* the non-water stressed baseline (lower baseline) and *ul* the non-transpiring upper baseline. The non-water-stressed baseline, which represents a fully watered crop, and the upper baseline, corresponds to a non-transpiring crop (stomata fully closed) (Yuan et al., 2004). Other approaches have involved extension of the CWSI concept to include other environmental variables. For example, indices that include net radiation as well as water vapour pressure deficit have been proposed (Jackson et al., 1981; Keener and Kircher, 1983). Value of CWSI varies from zero for no water stress to a maximum of one at severe stress (Hoffman et al., 1990).

Productivity response to water stress is different for each crop and this response is expected to vary with climate. Therefore, the critical values of CWSI should be determined for a particular crop in different climates and soils for use in yield prediction and irrigation management. A range of empirical studies have shown that there may be different non water stress baselines that can be used to quantify CWSI in the evaluation of plant water stress. Idso (1982) defined non water stressed baseline for 26 different species for clear sky conditions and found that these baselines were different for various phenological stages in certain crops. The lower baseline was determined for potato by Stark and Wright (1985). These baselines were strongly location dependent and perhaps species and variety dependent (Gardner et al., 1992). In pepper mint, the lower baseline and upper baseline were observed as zero and one (Ovcharova and Nedkov, 2005).

The CWSI was closely related to soil available water for wheat (Jackson et al., 1981) and sunflower (Nielsen and Anderson, 1989) and to plant water potential for cotton (Pinter and Reginato, 1982). A significant linear relationship was obtained between CWSI and leaf water potential for *Parthenium argentatum* (Nakayama and Bucks, 1983). Steele et al. (1994) obtained the highest yield for corn in fully irrigated treatment with an average CWSI value between 0.2 and 0.4. At a value of CWSI, 0.89 for maize, the crop showed symptoms of early senescence due to water stress (Wanjura and Upchurch, 2000). An average CWSI of 0.59 before irrigation times produced the highest yield in sunflower (Orta et al., 2002). In soybean, a value of 0.3 is indicated as the limit for obtaining the highest crop yield (Fernandes and Turco, 2003). Orta et al. (2003) defined the non water stressed baseline equation ($T_c - T_a = -1.2042\ VPD + 0.4716$) and stressed baseline value for watermelon and reported that an average CWSI of about 0.41 before irrigation will produce maximum yield.

Relationship between CWSI and soil water content in irrigated winter wheat and summer maize field was developed by Zhen-Hua et al., 2005 and Xiao et al., 2005. In potato, yield was directly correlated with seasonal CWSI values with a minimum of 0.49 and a maximum of 0.69 (Erdem et al., 2006). CWSI values before and after irrigation applications in potato were calculated to be 0.74 and 0.49 (Erdem et al., 2006). In cotton (Cohen et al. 2005; Sela et al. 2007) and grapevine (Moller et al., 2007), CWSI was developed to measure water stress. CWSI obtained from continuous nadir view measurements with infrared thermometers was a good and very sensitive indicator of water stress in pistachio (Testi et al., 2008). Infrared thermal imagery using CWSI was also found to be effective in timely determination of plant water stress in apple and peach orchards (Giuliani et al., 2001) and olive orchards (Canto et al., 2006).

An average threshold CWSI value of 0.17 before irrigation produced the maximum yield and it could be used to initiate the irrigation for watermelon (Kirnak and Dogan, 2009). In bermudagrass, average seasonal CWSI values were determined for 100 per cent, 75 per cent, 50 per cent and 25 per cent of irrigation treatment of pan evaporation as 0.086, 0.102, 0.165, and 0.394 respectively (Emekli et al., 2007). In cotton, the stressed range of CWSI was found to be 0.2 units less after irrigation (Meron et al., 2010). Change in CWSI in a corn field infested with weeds revealed that, under weedy conditions, CWSI values were high and in weed free conditions it was low (Edalat et al., 2010).

2.2. CWSI for irrigation scheduling

Irrigation scheduling typically strives to achieve an optimum water supply for maintaining crop productivity with the ultimate aim of soil water content being maintained close to field capacity (Jones, 2004). Successful irrigation depends upon understanding and utilizing irrigation scheduling principles to develop a management plan. Scheduling provides information, managers can use to develop irrigation strategies for each field on the farm. Irrigation scheduling methods are based on two approaches: a) soil measurements, and b) crop monitoring (Hoffman et al., 1990). Stomatal closure is the most sensitive among plant responses to soil water deficit, and hence it has the most potential as an indicator of irrigation requirement (Bates and Hall, 1981; Jones, 1990). Soil moisture methods were too variable for precise irrigation applications with the goal of minimizing water usage (Waldo, 2009). Irrigation scheduling based upon crop water status should be more advantageous, since crops respond to both the soil and aerial environment (Nielsen and Gardner, 1987; Nielsen, 1990; Yazar et al., 1999).

Much research has been done to evaluate the application of the CWSI in irrigation scheduling for different crops in different places. In cotton, yield showed first signs of decline when CWSI increased above 0.2. At this condition, irrigation should be applied (Reginato and Howe, 1985). Average value of CWSI, at which plants give maximum yield, was calculated for different varieties of cotton by different scientists (Wanjura et al., 1984; Fangmeier et al., 1989; Odemis and Bastug, 1999; Kirnak et al., 2005; Gonzalez-Dugo et al., 2006).

For large irrigation districts, irrigation scheduling using CWSI may be an economical option for minimizing water use and maximizing crop yield (Gonzalez-Dugo et al., 2006). CWSI models were found to be very effective in irrigation scheduling in maize (Clawson and Blad, 1982; Gencoglan and Yazar, 1999; Yazar et al., 1999; Steele et al., 2000; Irmak et al., 2000; Payero and Irmak, 2006), wheat (Alderfasi and Nielsen, 2001; Yuan et al., 2004; Wang et al., 2005, Gontia and Tiwari, 2008), vegetables (Cremona, et al., 2004; Erdem et al., 2006) and other plants (Ajayi and Olufayo, 2004; Payero et al., 2005; Wen-zhong et al., 2007). For water melon, maximum water use efficiency and irrigation water use efficiency were obtained when CWSI was 0.6 (Erdem et al., 2005). An average threshold CWSI value of about 0.51 before irrigation produced the maximum yield for broccoli (Erdem et al., 2010).

2.3. Effect of water stress in trees

When plants lose more water from the aerial part than they can replace via root uptake they exhibit water deficit, which can induce wilting, damage to cell membranes and ultimately, cell death. Severe water stress is the dominant factor that limits the establishment of seedlings in the field, especially in the regions of erratic rainfall which diminish the success of seedlings that are planted out. Water stress tend to reduce pre-dawn leaf water potential, which further induced stomatal closure and reduced gas exchange (Pereira et al., 1986; Kramer and Boyer, 1995; Nilsen and Orcutt, 1996; Lambers et al., 1998). Some plants possess certain adaptations to maintain a minimum water status to reduce the effect of low water content in cells.

The effects of water stress in the growth and development of forest trees is described by many authors (Kozlowski and Davies, 1975; Parsons, 1982; Kozlowski, 1982; Pereira et al., 1986; Pereira and Riekerk, 1990; Abebe, 1994; White et al., 1996; James and Bell, 2000; White et al., 2000; Burgess et al., 2001 etc.). Environmental factors affecting seedling development and survival (e.g. light, water, nutrients, temperature and other plants or enemies) can severely limit the recruitment dynamics of plant population (Ray and Alcantara, 2006). It is generally accepted that seedlings are less tolerant to unfavorable environments due to their small size, shallow roots and minimal capacity for resource storage (Li et al., 2000). A high mortality often occurs in the seedling establishment and juvenile growth stages, which may be critical for persistence and distribution of a population (Zhang et al., 2004). Plant water status controls the physiological processes and conditions which determine the quality and quantity of growth (Kramer, 1969). Water deficit affects nearly all the plant growth processes and the stress response depends upon the intensity, rate, and duration of exposure and the stage of crop growth (Brar et al., 1990). These stress responses may become apparent as changes in growth rate, leaf shape or biomass allocation (Gross, 1984; Tripathi and Khan, 1990; Saverimuttu and Westoby, 1996; Broncano et al., 1998; Rincon and Chapin, 1998; Guerfel et al., 2008). Tremendous seedling mortality occurs annually during initial stages of seedling establishment because of recurrent and periodic or sustained internal water deficit (Kozlowski, 1968).

Physiological and morphological changes occur in plants in response to severe water stress or drought (McKersie and Leshem, 1994; Nilsen and Orcutt, 1996; Lambers et al., 1998). Cannel et al. (1978) correlated reduced seedling growth of pine seedlings with water stress. Drought limits plant growth production more than any other environmental stresses (Zhu, 2002). Seedlings of Eucalyptus exposed to drought resulted in considerable dieback (Pohjonen, 1989; Abebe, 1994, Gindaba, 2004). An experiment was conducted to compare the effect of drought in one month old seedlings of *Albizzia lebbek, Dalbergia sissoo, Leucaena leucocephala, Shorea robusta* and Tectona *grandis*. Seedlings of all five species showed a decrease in seedling height with a maximum reduction in *L. leucocephala* (75.8 per cent) and minimum in *A. lebbek* (53.8 per cent) (Rao et al., 2008). Growth and survival of the seedlings decreased with increasing water stress in *Pinus roxburghii* (Saxena and Nautiyal, 2001). As saplings, Eucalyptus are more vulnerable to drought, which often reduces survival rates during establishment in the field (Gindaba et al., 2004; Garau et al., 2008; Rolando and Little, 2008). The observations of Bala et al. (2003) also indicated that there were significant differences in the growth parameters in the seedlings of *Acacia nilotica, Eucalyptus camaldulensis* and *Dalbergia sissoo* grown under severe water stress. High soil water availability facilitate nutrient accumulation, leaf growth, leaf area and number of leaves which convert more solar energy and fix more CO_2 to produce more photosynthates, and thus greater growth and biomass production (Ceulemans et al., 1993). Sufficient soil water availability maintains cell turgidity and increased leaf size and the overall biomass in poplars (Souch and Stephens, 1998).

2.3.1. Chlorophyll content and water stress

Severe drought causes rupture of chloroplast and disintegration of chlorophyll molecules. Water stress destroys chlorophyll present in the mesophyll cells than from the bundle sheath cells (Randall et al., 1977). There are reports about decrease of chlorophyll in the drought stress conditions (Beltrano and Ronco, 2008; Nikolaeva et al., 2010). The total chlorophyll, chlorophyll *a* and chlorophyll *b* contents of the leaves of *Pinus roxburghii* decreased with increasing water stress (Saxena et al., 2001). Ashraf et al. (1994) reported that drought stress will reduce concentration of chlorophyll b more than chlorophyll a. However there are reports which show that drought stress have no effect on chlorophyll concentration (Kulshreshtha et al., 1987).

2.3.2. Photosynthesis and water stress

The photosynthetic rate of the leaf is less responsive to mild water stress compared to leaf expansion. However, water stress usually reduce rate of leaf photosynthesis. Reduction in photosynthesis in response to water stress was reported in many crops and tree species (Rajendrudu and Naidu, 1998) which ultimately cause a reduction in plant growth (Majken et al., 2005). Decrease in photosynthesis may be because of damage of cellular structures (Kramer and Boyer, 1995; Tang et al., 2002) or due to reduction in chlorophyll concentration (Castrilo and Calcagno, 1984; Deborah and Bruce, 1998; Mohsenzadeh et al., 2005). Due to increased drought resistance, the rate of reduction was lowest in seedlings of *Leucaena leucocephala* and *Tectona grandis* compared to that of *Albizzia lebbek* (Rao et al, 2008). Severely water stressed two year old *Olea europaea* plants showed complete inactivation of photosynthetic activity (Angelopoulos et al., 1996; Xiloyannis et al., 1999). Two year old olive trees showed 83.8 per cent decrease in net photosynthesis after 60 days of withholding irrigation (Boughalleb and Hajlaoui, 2011). Cornic (2000) assumed that these decrease in photosynthesis is due to blocking of stomata followed by decreased relative cell water content.

2.3.3. Relative growth rate and water stress

Drought often cause a drastic reduction in relative growth rate as it decrease turgor and cause cells to shrink. Six month old seedlings of *Hopea odorata* and *Mimusops elengi* showed low relative growth rate under water stressed conditions (Zainudin et al., 2003). Relative growth rate decreased by 33.8 per cent with increasing water stress in two year old olive trees (Boughalleb and Hajlaoui, 2011). But in an experiment using one month old seedlings of *Albizzia lebbek*, *Dalbergia sissoo*, *Leucaena leucocephala*, *Shorea robusta* and *Tectona grandis*, under water stress, *S. robusta* and *T. grandis* showed a decreased relative growth rate and net assimilation rate but *A. lebbek*, *D. sissoo* and *L. leucocephala* showed a reverse pattern probably due to better drought tolerance (Rao et al., 2008).

2.3.4. Height and water stress

Water stress affect height growth as it reduces turgor pressure, the most important factor determining cell division and elongation. Water limited productivity of plants depends on the total amount of water available and on the water use efficiency of the plant. Restricted water supply decreased height of different Eucalyptus species (Rawat et al., 1985; Myers and Landsberg, 1989; Pereira et al., 2002). A drastic reduction in height as response to low moisture was observed in seedlings of *Pseudotsuga menzeissi*, *Pinus contorta*, and *Picea glauca* (Driessche, 1991). Irrigated seedlings of *Acacia mangium* had a height of 55.7 cm whereas the moisture stressed plant was only 40.2 cm tall (Awang and Chavez, 1993). Significant difference in height of *Dalbergia sissoo* seedlings observed due to variations in soil water availability at different irrigation levels (Singh and Singh, 2009). A study on six month old seedlings of *Hopea odorata* and *Mimusops elengi* by Zainudin et al. (2003) indicates height growth of seedlings were greatly depressed by water stress. A similar pattern was observed in two year old olive trees (*Olea europaea*) (Roussos et al., 2010).

2.3.5. Collar diameter and water stress

As water stress negatively affects the overall plant growth, it reduces collar diameter also. Significant differences in collar diameter observed in seedlings of *Eucalyptus globulus* (Pereira et al., 2002), *Dalbergia sissoo* (Singh and Singh, 2009), *Hopea odorata* and *Mimusops elengi* (Zainudin et al., 2003) due to variations in soil water availability at different irrigation levels. Similar result was obtained in sandal seedlings also (Hiremath, 2004).

2.3.6. Number of leaves and water stress

Leaf is the organ most responsive to environmental conditions (Nevo et al., 2000). Reduction in leaf area can be considered a first line of defense against drought as it improves the plant's fitness in water limited environment. Water stress was observed to reduce total number of leaves, specific leaf area and total leaf area of plants to effectively conserve available soil moisture. In seedlings of *Eucalyptus maculata* and E. *brockwayi* intensity of applied water stress did not affect the proportion of total assimilate allocated to foliage production, but it reduced the total leaf area, through a fivefold reduction in number of leaves, and through a 20 per cent reduction in average leaf size (Myers and Landsberg, 1989). Prolonged periodic water stress reduced the amount of foliage by 90 per cent in *Fagus sylvatica* (Cermak et al., 1993). A significant decrease in the average single leaf area and an increase in specific leaf area with increasing water stress in seedlings of *Albizzia lebbek*, *Dalbergia sissoo*, *Leucaena leucocephala*, and *Tectona grandis* but *Shorea robusta* showed a reverse pattern (Rao et al., 2008).

2.3.7. Root-shoot allocation and water stress

Water deficiencies can lead to shift in root-shoot allocation patterns in plants (Waring, 1991). They tend to accumulate more biomass to growing root tips in search of water in deeper soil layers. Deeper root growth into wet soil is considered as the second line of defense mechanism against drought followed by reduction in total leaf area. Moisture stress negatively affected shoot growth than root growth and resulted in an increased root-shoot ratio in long leaf pine and slash pine seedlings (Pessin, 1939). Similar observation was obtained in ten week old seedlings of *Acacia mangium* (Awang and Chavez, 1993). Greater allocation of dry matter to roots in cuttings of balsam spire poplar (*Populus balsamifera x Populus trichocarpa*) was observed when plants were subjected to reduced soil moisture availability (Ibrahim et al., 1997). Compared to root length, a significant reduction was reported in shoot height in *Erythrina variegata* (Muthechelian et al., 1997). Root-shoot ratio was reported to be higher in drought affected saplings of Eucalyptus than the normal (Rose et al., 1990; Ngugi et al., 2004). The same pattern was observed in sandal (Hiremath, 2004). An increase in the length of primary root experiencing moderate water stress was observed, where as the root length was minimum in severely stressed seedlings of *Pseudotsuga menziesii* (Smit and Driessche, 1992). Root-shoot ratio of *Hopea odorata* and *Mimusops elengi* seedlings on a weight basis was relatively higher under water stressed conditions compared to well watered control plants (Zainudin et al., 2003). Similar observations were made in seedlings of *Dalbergia sissoo* (Singh and Singh, 2009).

2.3.8. Dry matter production and water stress

Water deficit will have a negative impact on dry matter accumulation in plants as it impairs with many of the physiological processes which determines growth like photosynthesis, respiration, enzyme activity etc. Reduction in total seedling dry matter yield under water stress conditions has been reported in *Quercus leucotrichophora* and *Pinus roxburghii* (Rao and Singh, 1984) and in *Quercus floribunda* and *Cupressus torulosa* (Rao, 1988). Drought stress affected seedlings of *Pseudotsuga menzeissi*, *Pinus contorta*, and *Picea glauca* by significantly reducing dryweight (Driessche, 1991). Similar results are shown in *Santalum album* (Hiremath, 2004). In different acacia species also the reduction in biomass has been reported (Phillips and Riha, 1993; Kireger and Blake, 1994). Dry biomass decreased at very high stress in seedlings of *Albizzia lebbek, Dalbergia sissoo, Leucaena leucocephala, Shorea robusta* and *Tectona grandis* with maximum reduction in *L. leucocephala* (99.8 per cent) and minimum in *A. lebbek* (81.6 per cent) (Rao et al, 2008). In saplings of Eucalyptus the reduction was reported as 45 per cent (Rose et al., 1990). A clone of *Eucalyptus nitens* subjected to a series of drought cycles senesced leaves acropetally, and reduced biomass accumulation by half when compared with control plants (Mokotedi et al., 2000). Water stressed plants accumulated half the leaf biomass of control plants in *Eucalyptus microtheca* (Tuomela, 1996; Li et al., 2000; Li and Wang, 2003) and *Eucalyptus globulus* (Metcalfe et al., 1990).

2.4. Response of teak under water stress

Teak is one of the most valuable timbers in the world. It has been planted extensively in areas with warm climate. Teak is considered as an attractive, light but strong wood material with great resistance against fungi, humidity and insect damages. Without remarkable splitting, cracking, warping or physically altering shape of wood material, and is found to be a user-friendly material for processing (CAB, 2000). It is very sensitive to drought especially in the first growing season leading to large scale mortality in nurseries (Kadambi, 1972). According to studies of water consumption by Kallarackal and Somen (1992), a twelve year old teak consumes 83 litres of water per day in leafy season. During the dry season, the water consumption is negligible because of the deciduous state. Under very dry conditions, teak is usually stunted and shrubby. Under very moist conditions, the tree is large and fluted and usually behaves like a semi-evergreen species. It has been reported that for the production of high quality wood with optimum growth, moisture conditions (as expressed by annual rainfall) should be between 1,200 and 2,500 mm with a marked dry season of 3-5 months (Kaosaard, 1981). Rajendrudu and Naidu (1998) compared the effect of controlled irrigation in three month old seedlings. They found that there was no significant change on height growth, rate of leaf production and internodal elongation during the first week after complete withholding of irrigation. During the second week, a 50 per cent reduction was observed in growth rate and during the third week, growth rate became negligible. After rewatering, these plants regained normal growth potential which was comparable to those of well watered plants. Net photosynthetic rate showed no reduction for two weeks after withholding the irrigation, later started declining but regained after rewatering (Rajendrudu and Naidu, 1998).

2.5. Response of mahogany under water stress

Mahogany receives special attention among trees used for raising plantations and afforestation purposes because of its high commercial value. It is raised as pure plantation, mixed plantation and also in agroforestry. However, this species is still poorly studied in relation to its management in plantations and its physiological responses to environmental stresses. Webb et al. (1984) suggest that mahogany can tolerate a dry season up to four months. A study conducted by Cordeiro et al. (2009) to study drought response of mahogany seedlings reported that seedlings showed a significant reduction in leaf and leaflet number and total leaf area but stem height, diameter and rate of photosynthesis remained unaffected due to water stress.

Both teak and mahogany require a relatively long nursery period lasting about one year. Standardization of nursery techniques is necessary in any afforestation programme as expenditure on nursery is a major portion of plantation cost. The cost can however, be reduced by evolving suitable and desired nursery practices on scientific lines (Bahuguna and Lal, 1992). A goal of forest tree nursery operations is to produce high quality seedlings with target characteristics capable of maximum performance potential after outplanting into the field (Rose et al., 1990). During initial stages of seedling establishment tremendous seedling mortality occurs annually because of recurrent and periodic or sustained internal water deficit (Kozlowski, 1968). The balanced water content in soil allowing a suitable level of soil air indirectly controls seedling growth (Tripathi and Saxena, 1986). Determination of optimal watering frequency and water reaquirement for teak and mahogany seedlings is very essential. Reviewing the literature, it was noted that studies regarding crop water stress index on tropical tree species were scanty. Investigations regarding effect of water stress in teak and mahogany seedlings were also less. Hence the present study is oriented to explore the use of CWSI to predict water stress in tree seedlings to provide a method for early detection of water stress.

MATERIALS AND METHODS

MATERIALS AND METHODS

3.1. Location

The present study "Modeling crop water stress index (CWSI) in tree seedlings" was carried out at College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur district, Kerala located at 10° 31'N latitude and 76° 13'E longitude with an elevation of about 22.25 m above mean sea level. The study was conducted during 2010-2011.

3.2. Climate

The area enjoys a warm humid tropical climate with distinct summer and rainy season. It had received a total rainfall of 3018.4 mm during 2010 and 87.5 mm till the end of March in 2011. Other climatic parameters collected during the observation period are given below (Table 1, Figure 1). It was collected from agrometeorological observatory, COH, Vellanikkara.

3.3. Methodology

The experiment was conducted to model crop water stress index in the following tree seedlings

1. Teak (*Tectona grandis* L. f)
2. Mahogany (*Swietenia macrophylla* King.)

Six months old seedlings were transplanted in polythene bags of size 35 cm x 10 cm containing 1:2:3 mixture of soil, sand and cow dung. These seedlings were grown under a rain out shelter (10 m x 5 m x 2 m) throughout the experimental period to prevent entry of water from outside. The structure was provided with gabled roof covered with transparent polyethylene film of 0.1 mm thickness. The sides of the rain out shelter were constructed using wooden and bamboo poles and covered with tarpaulin sheet to prevent the entry of rainwater into it.

Table 1. Weather parameters from September 2010- March 2011

Year	Month	Temperature (˚C) (Max.)	Temperature (˚C) (Min.)	R.H (per cent)	SSH (Hours)	WS (Km/hr)	Evaporation (mm)
2010	September	30.5	23.1	83	125.6	2.2	4.6
	October	29.7	22.4	85	129.5	2.13	3.95
	November	30.4	22.5	81	122.5	3.53	3.83
	December	30.9	22	70	206.7	5.00	4.56
2011	January	32.7	22.2	58	263	6.31	5.25
	February	33.7	22	55	239.1	5.29	5.19
	March	34.8	23.9	85	268.9	4.13	5.46

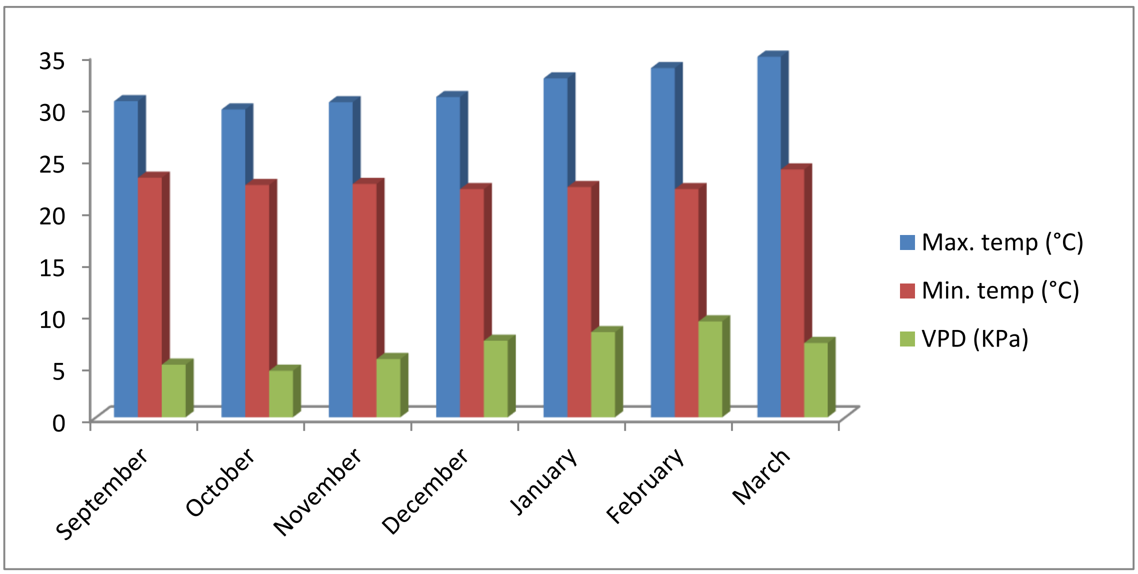

Figure 1 Mean maximum temperature, mean minimum temperature and vapour pressure deficit (VPD) during September 2010 to March 2011

3.3.1. Experimental layout

The experiment used a completely random design (CRD) with four different levels of irrigation as treatments. Each treatment comprised of 125 seedlings. Plants within each block were arranged without any inter-row spacing, whereas a gap of 1 m was given between each block. Observations were initiated after six months of seedling establishment.

3.3.2. Irrigation schedule

Irrigation was provided once in every seven days. Daily evapotranspiration was calculated and treatments IW/ET=1, IW/ET=0.6 and IW/ET=0.3 were irrigated with 100, 60 and 30 per cent of cumulative evapotranspiration calculated on daily basis. IW/ET=0, a treatment without any irrigation was maintained as control. An additional 5 per cent was given to cope up with losses during irrigation. For calculation of reference evapotranspiration (ETo), a software programme DAILYET – Evapotranspiration calculator – developed by Dr. Tim Hess and Stein of Cranfield University was used (available at http://www.cranfield.ac.uk). It estimates daily reference evapotranspiration (ETo) based on several equations available in the software like Penman, Penman Monteith, FAO Modified Penman or Penman openwater. The input data required are maximum and minimum air temperature, relative humidity, sunshine hours and wind speed which were collected from agro meteorology observatory, COH, Vellanikkara. Out of the available equations, FAO modified Penman's equation was used for calculating reference evapotranspiration which is defined for a hypothetical grass crop with an assumed height of 0.12 m, a fixed surface resistance ($70 sm^{-1}$) and an albedo (0.23) which is actively growing and adequately watered (Allen et al., 1998).

a. Teak seedlings

b. Mahogany seedlings

c. Rain out shelter

d. Seedlings arranged inside rain out shelter

Plate 1. Experimental materials

Table 2. Treatment combinations and levels of irrigation provided

Treatment	Irrigation levels (in per cent of cumulative crop evapotranspiration)
IW/ET=1	Treatment with irrigation at 1.0 IW/ET
IW/ET=0.6	Treatment with irrigation at 0.3 IW/ET
IW/ET=0.3	Treatment with irrigation at 0.6 IW/ET
IW/ET=0 (control)	Treatment with no irrigation

3.4. Observations

3.4.1. Physiological observations

a. Canopy temperature

Canopy temperature and the corresponding air temperature were measured using a hand held infrared thermometer (Agri-Therm II 6110.4ZL). Systematic calibrations of the instrument were done in the laboratory during the study. Temperature measurements were done after 11:00 am, when the differences in temperature between stressed and non-stressed crops are most readily detected (Gardner et al., 1981). Leaves on the upper most part of the plant, fully expanded and completely exposed to full sunlight were selected for temperature measurements. Fifteen observations from each treatment were recorded each day. Vapour pressure deficit (VPD) of the air was calculated using the procedure given by Allen et al. (1998).

$$es = 0.6108 \exp \frac{(17.27 \times T_a)}{(T_a + 237.3)}$$

$$ea = es \times (RH/100)$$

$$VPD = es - ea$$

es = saturation vapor pressure (kPa)

T_a= air temperature (°C)

ea = actual vapour pressure (kPa)

RH = relative humidity (%)

VPD = vapour pressure deficit (kPa)

b. Development of baseline equations for canopy air temperature difference (CATD)

The treatments IW/ET=1 and IW/ET=0 were selected to develop the lower baseline (minimum stress baseline) and upper baseline (maximum stress baseline) respectively. Canopy air temperature difference (CATD) was calculated separately for both well irrigated and non irrigated treatments and plotted against VPD of the corresponding day. The equation showing the relation between lower baseline and upper baseline of CATD and VPD were thus developed from the scatter diagram by linear regression technique. The other two treatments with two different irrigation levels (IW/ET=0.6 and 0.3) were designed to evaluate different threshold CWSI values for scheduling the irrigation.

c. Calculation of crop water stress index (CWSI)

CWSI was calculated separately for each treatment using the equation (Idso et al., 1981)

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}}$$

T_c = canopy temperature

T_a = air temperature

ll = non-water stressed baseline

ul = non-transpiring upper baseline

d. Chlorophyll content

The plants were evaluated each week in order to measure the effect of water stress in chlorophyll content using chlorophyll meter (SPAD-502, Minolta). Randomly selected ten mature leaves were used for this purpose.

e. Standardization of SPAD values

SPAD value was standardized for Chlorophyll a, b and total chlorophyll content using the method of Starner and Hardley (1967). Leaf discs of 1 g each were taken from five fully expanded leaves. Leaf sections were ground in 80 per cent acetone. The extract was filtered using Whattman No.1 filter paper and made up to 25 ml in a volumetric flask using 80 per cent acetone. The absorbance was read at 663 and 645 nm wave length in a spectrophotometer. Using the absorption coefficients, the amount of chlorophyll was calculated using the empirical formula:

Chl a, mg/g tissue = 12.7(OD at 663)-2.69(OD at 645) x V/1000 xW

Chl b, mg/g tissue = 22.9(OD at 645)-4.68(OD at 663) x V/1000 xW

Total chlorophyll, mg/g tissue = 20.2 (OD at 645) + 8.02(OD at 663) x V/1000 xW

Where,

OD = Optical Density

V= Final volume of chlorophyll extract in 80 per cent acetone (ml)

W= Fresh weight of tissue extracted (g)

f. Crude protein content

Crude protein content in leaves was estimated using Lowry’s method of protein estimation (Lowry et al., 1951) and it was approximated to the Rubisco

Plate 2 Measurement of relative chlorophyll content using SPAD meter

content. For estimating crude protein, 500 mg of leaf samples were homogenized in 10 ml distilled water by means of pestle and mortar. The supernatant was collected after centrifugation. Then 0.1 ml and 0.2 ml of supernatant was pipetted into two different test tubes and made up to 1ml by adding distilled water. A blank was set up with 1.0 ml distilled water. Then 5 ml of alkaline $CuSO_4$ reagent was added to each tube and mixed well. After 10 minutes, 0.5 ml of Folin-Ciocalteau reagent was added, mixed well and incubated at room temperature in the dark for 30 minutes. Blue color developed was read at 660 nm in a spectrophotometer.

Stock solution of protein was prepared by dissolving 50 mg of bovine serum albumin in 50 ml of distilled water. Working standard of bovine serum albumin was prepared by making up 10 ml stock to 50 ml with distilled water. Then 0.2, 0.4, 0.6, 0.8 and 1.0 ml of the working standard were pipetted into a series of test tubes and the intensity of color developed was read as in the case of sample to develop a standard curve. The amount of protein was calculated using the standard curve and expressed in mg/ml.

g. Relative growth Rate (RGR)

Relative growth rate was estimated using the formula given below and expressed in g g^{-1} day^{-1}

$$RGR = \frac{\ln W_2 - \ln W_1}{T_2 - T_1}$$

ln = natural logarithm

W_2 = final dry weight

W_1 = initial dry weight

T_2 = final time period

T_1= initial time period

3.4.2. Biometric observations

Five plants were randomly taken out from each treatment combination biweekly beginning at 14 days after start of treatment and continued up to six months.

Seedlings were destructively sampled. Stem, root and leaf portion were separated. Observations on height, collar girth, number of leaves, shoot weight, root length, root weight, shoot root length ratio and shoot root biomass ratio were measured.

a. Height

Height was measured from collar region to the terminal bud using a meter scale and expressed in cm.

b. Collar diameter

Collar diameter was measured using a digital vernier calliper, and expressed in mm. Diameter was recorded for the same plants in which plant height were measured.

c. Number of leaves

The leaf number was counted for each seedling.

d. Fresh weight of shoot and root

Shoot weight and root weight of each seedling was recorded by electronic balance and expressed in g.

e. Root length

Root length from the collar region to the tip of the longest root was measured using a meter scale and recorded in cm.

f. Shoot-root length ratio

Shoot-root length ratio was worked out at weekly intervals using the formula

$$\text{Shoot -root length ratio} = \frac{\text{Shoot length (cm)}}{\text{Root length (cm)}}$$

g. Shoot-root biomass ratio

After recording fresh weights of stem, leaves and roots samples were oven dried at 60°C-80°C overnight. Then the dry weight were recorded for shoots and roots separately and shoot-root biomass ratio was calculated using the formula

$$\text{Shoot-root biomass ratio} = \frac{\text{Shoot weight (g)}}{\text{Root weight (g)}}$$

3.4.3. Meteorological observations

Daily meteorological observations were recorded during the whole experimental period. Dry bulb temperature, wet bulb temperature, and relative humidity were noted from Stevenson screen, wind speed using a cup anemometer, sun shine hours from sun shine recorder established in the agrometeorological observatory, COH, Vellanikkara.

3.5. Statistical analysis

Data obtained were subjected to statistical analysis using SPSS (v 17). The tests used included ANOVA with post hoc testing using Duncan's multiple range tests (DMRT) and Regression.

RESULTS

RESULTS

The study on “Modeling crop water stress (CWSI) in tree seedlings” was carried out during the period 2010-2011 at College of Forestry, Kerala Agricultural University, Vellanikkara, Kerala, India.

Five hundred seedlings of two species – teak and mahogany were raised in polybags and maintained in a rain out shelter. Treatments were provided with four different sets of irrigation levels on weekly interval and different parameters were observed. For the first two months control seedlings were kept outside the rain out shelter and were getting rainfall. Later it was transferred to rain out shelter and maintained there to measure the level of stress occurred in the absence of any water supply. But observations on control treatment could not be continued up to the end of experiment because of mortality due to prolonged water stress. Symptoms of water stress occurred due to various irrigation regimes are given in Plate 3 and 4. The results of the experiment are given below.

4.1. Physiological observations

4.1.1. Canopy air temperature difference (CATD) (°C)

Effect of irrigation on canopy air temperature difference was observed. Canopy temperature was measured using a hand held infrared thermometer (Agri-Therm II 6110.4ZL). Corresponding air temperature was also recorded and canopy air temperature difference (CATD) was calculated separately for each treatments.

Teak

CATD for teak seedlings at various irrigation levels was calculated and described in Table 3. A daily comparison was also done for CATD for the consecutive days after irrigation. Teak seedlings from well watered treatments (IW/ET=1 and 0.6) showed negative CATD whereas treatments IW/ET=0.3 and IW/ET=0 showed positive CATD throughout the growing period. Well watered treatments IW/ET=1 and

a. Teak seedling under irrigation at IW/ET= 1

b. Teak seedling under irrigation at IW/ET= 0.6

c. Teak seedling under irrigation at IW/ET= 0.3

d. Teak seedling under irrigation at IW/ET=0

Plate 3 Visual symptoms of water stress on teak seedlings under different levels of irrigation after 3 months.

a. Mahogany seedling under irrigation at
under irrigation at IW/ET= 1
IW/ET= 0.6

b. Mahogany seedling

c. Mahogany seedling under irrigation at
under irrigation at IW/ET= 0.3
0

d. Mahogany seedling
IW/ET=

Plate 4 Visual symptoms of water stress on mahogany seedlings under different levels of irrigation after 3 months.

0.6 were on par and were superior over IW/ET=0.3 and IW/ET=0 in CATD. There was no significant difference between CATD of IW/ET=0 and IW/ET=0.3. Canopy temperature of plants from treatments IW/ET=1 and 0.6 remained few degrees lesser than the air temperature on the day of irrigation and for few consecutive days. In IW/ET=0 and IW/ET=0.3, CATD remained higher throughout the week and the maximum CATD obtained was 3.8°C. Even though the difference in CATD within the treatment was not significant, there was increase in CATD towards the end of the week. In IW/ET=1 and 0.6, maximum value were obtained for the next day after irrigation.

Mahogany

Canopy air temperature difference at various irrigation levels for mahogany is given in Table 4. In mahogany, CATD of IW/ET=0 and IW/ET=0.3 were positive whereas in well watered treatments (IW/ET=1 and 0.6) CATD remained negative throughout the entire growing period. No significant difference was observed among IW/ET=1 and 0.6 in CATD. Performance of treatment IW/ET=0.3 was inferior over IW/ET=0 up to sixth day but increased and remained on par with IW/ET=0 on seventh day. CATD of treatment IW/ET=1 and IW/ET=0 remained without any significant difference all over the week whereas CATD of other two treatments, IW/ET=0.6 and 0.3 were found to be increasing during the course of time after irrigation. CATD of IW/ET=0.6 increased from -4.2 to -2.5 and for IW/ET=0.3 it increased from 1.6 to 3.8. For IW/ET=0, CATD was approximately 5°C and for IW/ET=1 it was between -5.3 and -4.1°C.

4.1.2. Development of baseline equations for CATD

Treatment IW/ET=1 was used to determine the lower (non-stressed) baseline for CATD and non irrigated fully water stressed treatment IW/ET=0 was used for

Table 3 Canopy air temperature difference (CATD) (°C) of teak seedlings in response to different irrigation levels

Treatments	Days after irrigation							
	DAY 1	DAY 2	DAY 3	DAY4	DAY 5	DAY 6	DAY 7	SEm$\pm$
IW/ET=1	-4.5^{b}	-4.6^{b}	-3.9^{b}	-3.7^{b}	-4.1^{b}	-3.7^{b}	-3.2^{b}	2.6^{ns}
IW/ET=0.6	-3.3^{b}	-3.6^{b}	-2.7^{b}	-2.7^{b}	-3.1^{b}	-2.4^{b}	-2.3^{b}	2.7^{ns}
IW/ET=0.3	2.4^{a}	2.7^{a}	3.2^{a}	3.4^{a}	3.3^{a}	3.4^{a}	3.8^{a}	2.7^{ns}
IW/ET=0	3.6^{a}	3.4^{a}	3.4^{a}	3.8^{a}	3.4^{a}	2.8^{a}	3.3^{a}	3.7^{ns}
SEm$\pm$	0.9^{*}	0.8^{*}	0.7^{*}	0.8^{*}	0.8^{*}	0.8^{*}	0.9^{*}	

* Significant at 0.05 levels; Values with similar superscript along the column do not differ significantly; ns- non significant at 0.05 levels

Table 4 Canopy air temperature difference (CATD) (°C) of mahogany seedlings in response to different irrigation levels

Treatments	Days after irrigation							
	DAY 1	DAY 2	DAY 3	DAY4	DAY 5	DAY 6	DAY 7	SEm$\pm$
IW/ET=1	-5.3^{c}	-5.3^{c}	-5.0^{c}	-4.9^{c}	-4.8^{c}	-4.3^{c}	-4.1^{b}	2.6^{ns}
IW/ET=0.6	-4.2^{c}	-4.2^{c}	-3.6^{c}	-3.6^{c}	-3.5^{c}	-3.0^{c}	-2.5^{b}	2.8^{*}
IW/ET=0.3	1.6^{b}	1.7^{b}	2.4^{b}	2.6^{b}	2.7^{b}	3.2^{b}	3.8^{a}	2.8^{*}
IW/ET=0	4.9^{a}	4.9^{a}	5.0^{a}	5.3^{a}	4.9^{a}	5.6^{a}	5.5^{a}	3.6^{ns}
SEm$\pm$	4.6^{*}	4.2^{*}	3.8^{*}	3.7^{*}	4.1^{*}	4.2^{*}	4.7^{*}	

* Significant at 0.05 levels; Values with similar superscript along the column do not differ significantly; ns- non significant at 0.05 levels

determining upper baseline for CATD. CATD of these two treatments were plotted against vapour pressure deficit (VPD) of the corresponding day. The equation showing the relation between lower baseline and upper baseline of canopy air temperature difference and VPD were developed from this scatter diagram by linear regression technique.

For teak the lower baseline was determined as CATD = -1.01VPD+2.8 (R^2=0.86) and the upper baseline equation was CATD = -0.05VPD+5.1 (R^2=0.61) (Figure 2). For mahogany, lower baseline equation was CATD = -0.25VPD-2.9 (R^2=0.79) and upper baseline equation was CATD = -0.01VPD+6.1 (R^2=0.58) (Figure 3). For both the species, upper limit of CATD was found to be highly fluctuating. For developing upper baseline, the average values of CATD for the fully-stressed plants were used.

Crop Water Stress Index (CWSI)

In order to get an indirect measure of plant water stress, Crop Water Stress Index (CWSI) was determined. CWSI exploit the relationship between canopy air temperature difference (CATD) and vapour pressure deficit (VPD) of the air to give a relative measure of water stress in plants.

Teak

Pattern of variation in CWSI of teak over a week is given in Figure 4. Non irrigated IW/ET=0 and IW/ET=0.3 showed a greater value (greater than 0.5). Well irrigated treatments IW/ET=1 and 0.6 had lower CWSI and the range of fluctuation was from -0.2 to 0.2. The entire range of CWSI in teak seedlings was found to be exceeding the theoretical 0 to 1 range and observed as -0.2 to 1. Irrigated treatments showed a slow increase in CWSI to a maximum value just prior to the next irrigation application as the soil water in the crop root zone was depleted. But CWSI of non irrigated IW/ET=0 remained without much fluctuation through the experimental period.

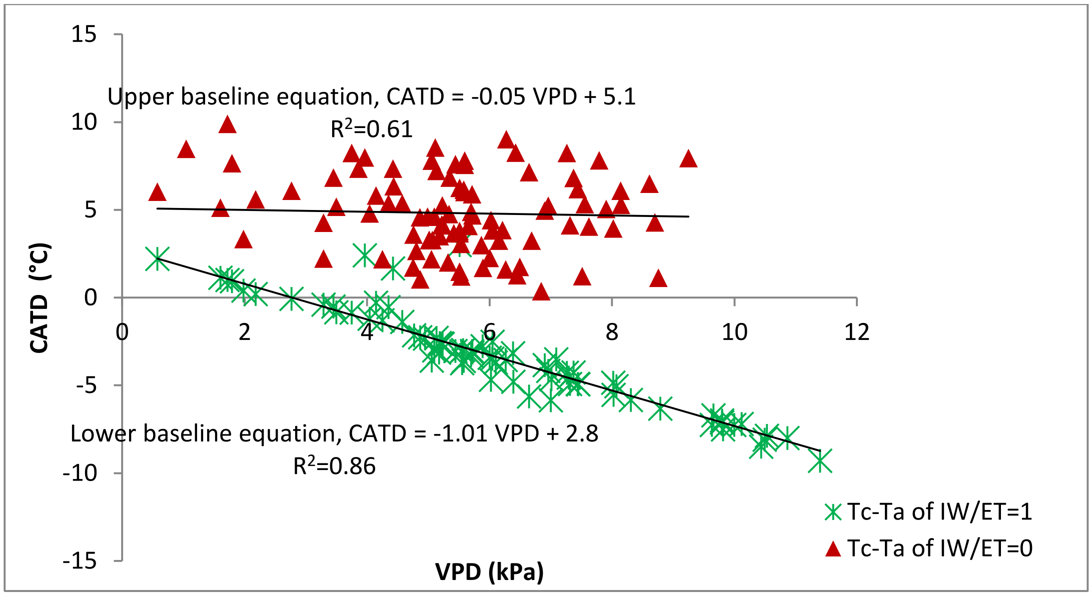

Figure 2 Upper and lower baseline for canopy air temperature difference (CATD) in teak

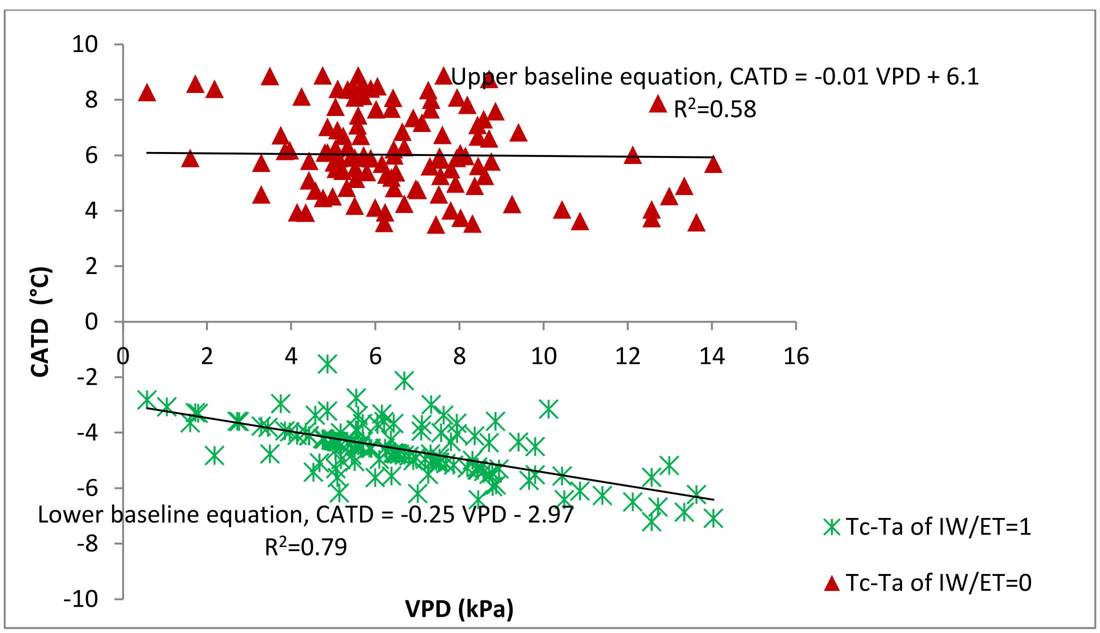

Figure 3 Upper and lower baseline for canopy air temperature difference (CATD) in mahogany

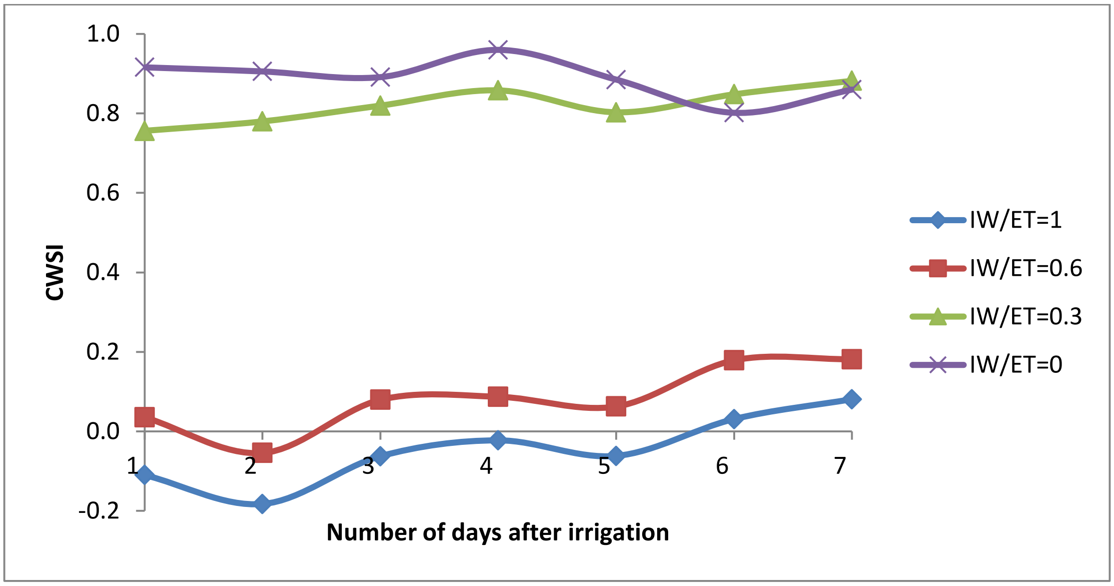

Figure 4 Crop water stress index (CWSI) of teak seedlings for 7 days after irrigation

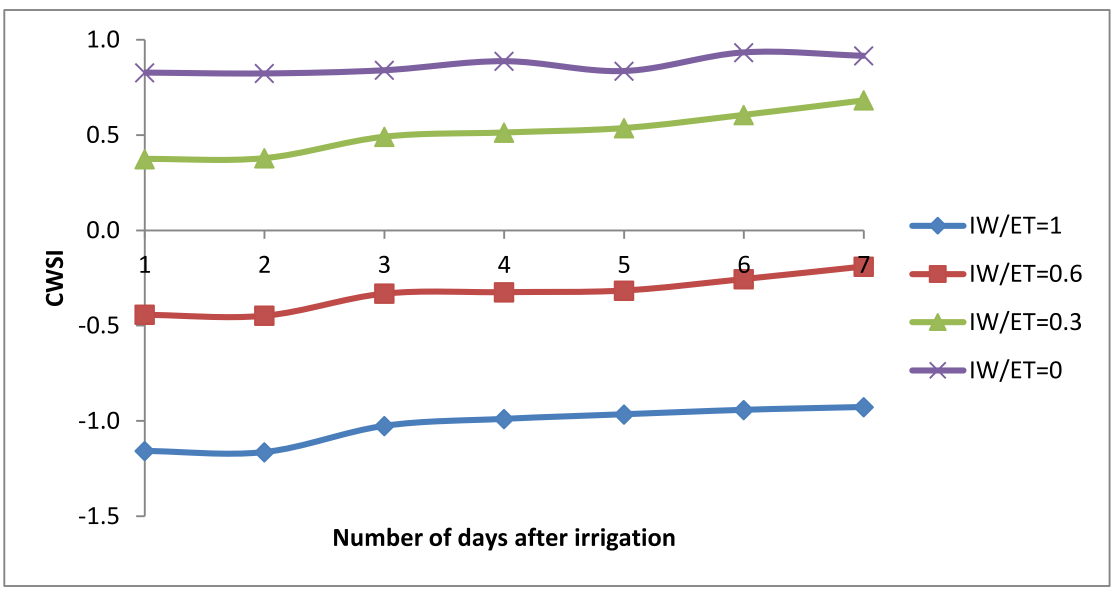

Figure 5 Crop water stress index (CWSI) of mahogany seedlings for 7 days after irrigation

Mahogany

Variation in CWSI among different treatments of mahogany seedlings is given in Figure 5. The overall range of CWSI in mahogany seedlings is -1.2 to 0.9. For IW/ET=1 CWSI ranged from -1.2 to -0.9. For IW/ET=0.6 it was -0.4 to -0.2. In IW/ET=0.3, the value ranged from 0.4 to 0.7 and in IW/ET=0 it fluctuated from 0.8 to 0.9. CWSI values in irrigated plots generally dropped following each irrigation application, and then found to be increasing to a maximum value prior to the next irrigation application. But CWSI of non irrigated IW/ET=0 remained without much fluctuation.

4.2.1. Chlorophyll content

Teak

Relative chlorophyll content was measured using chlorophyll meter (SPAD-502, Minolta). The observations revealed that significant reduction in chlorophyll content occurred during water stress in teak seedlings (Table 5, 6 and Figure 6). Water stressed IW/ET=0 treatment showed minimum chlorophyll content compared to the other treatments from the second week of treatment. At the end of six months of treatment relative chlorophyll content was minimum in treatment IW/ET=0.3 (0.45mg/g) followed by IW/ET=1 (3.78mg/g) and IW/ET=0.6 (4.38mg/g.)

Mahogany

The observation on chlorophyll content of mahogany seedlings is given in Table 7, 8 and Figure 7. Non irrigated IW/ET=0 had the minimum value of chlorophyll content throughout the observation period. After three months of treatment, IW/ET=0.3 showed a significant decline in total chlorophyll content. No significant variation was observed in between well irrigated treatments (IW/ET=1 and 0.6). At the end of six months IW/ET=0.3 had minimum chlorophyll content

Table 5 Effect of different levels of irrigation on chlorophyll content in teak seedlings after 100 days

Treatments	Chlorophyll content	
	(SPAD unit)	(mg/g)
IW/ET=1	43.2	3.81[a]
IW/ET=0.6	42.6	3.65[a]
IW/ET=0.3	38.7	2.44[ab]
IW/ET=0	36.7	1.82[b]
SEm$\pm$	---	0.6*

*Significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

Table 6 Effect of different levels of irrigation on chlorophyll content in teak seedlings after six months growth

Treatments	Chlorophyll content	
	(SPAD unit)	(mg/g)
IW/ET=1	43.0	3.78[a]
IW/ET=0.6	45.0	4.38[a]
IW/ET=0.3	32.2	0.45[b]
SEm$\pm$	---	0.9*

*Significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

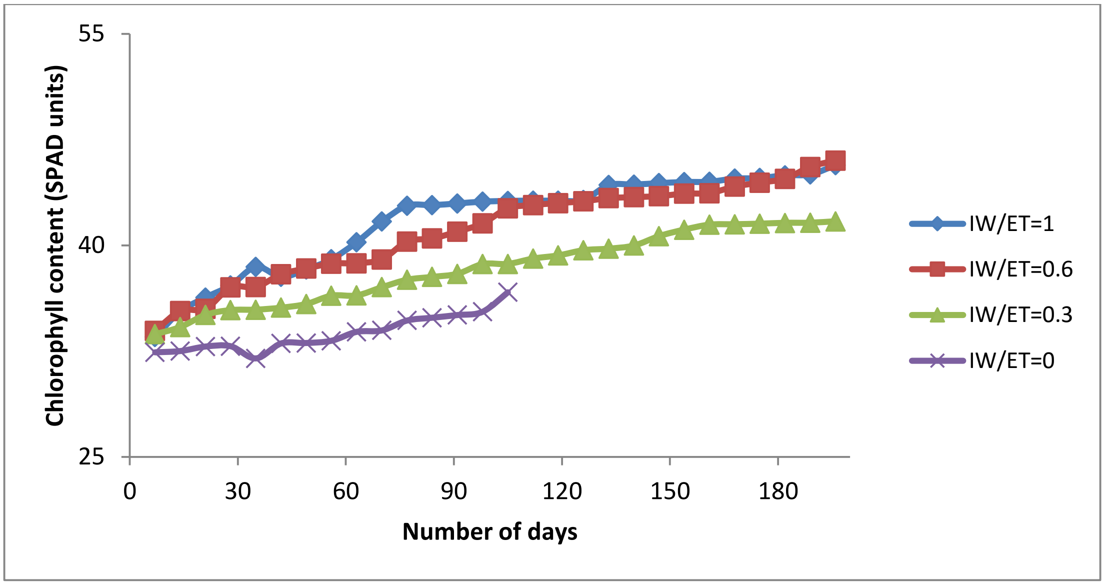

Figure 6 Effect of different levels of irrigation on chlorophyll content in teak seedlings

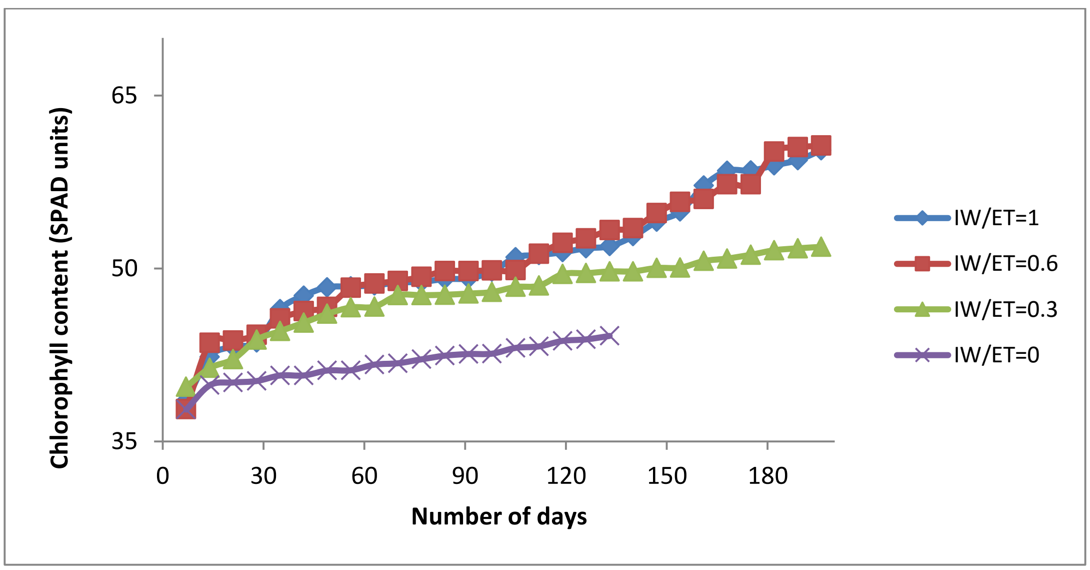

Figure 7 Effect of different levels of irrigation on chlorophyll content in mahogany seedlings

Table 7 Effect of different levels of irrigation on chlorophyll content in mahogany seedlings after 125 days

Treatments	Chlorophyll content	
	(SPAD unit)	(mg/g)
IW/ET=1	51.93	0.44[a]
IW/ET=0.6	53.32	0.45[a]
IW/ET=0.3	49.75	0.42[a]
IW/ET=0	44.15	0.37[b]
SEm±	---	0.04*

* Significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

Table 8 Effect of different levels of irrigation on chlorophyll content in mahogany seedlings after six months growth

Treatments	Chlorophyll content	
	(SPAD unit)	(mg/g)
IW/ET=1	58.9	0.51[a]
IW/ET=0.6	55.8	0.48[a]
IW/ET=0.3	44.6	0.37[b]
SEm±	---	0.1*

* Significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

(0.37mg/g). It was maximum in IW/ET=1 (0.51mg/g) followed by IW/ET=0.6 (0.48mg/g).

4.2.2. Crude protein content

Teak

Crude protein content in leaves was determined using Lowry's method of protein estimation (Lowry et al., 1951) and it was assumed to be equal to total Rubisco content. No significant difference was observed in total crude protein content of teak leaves at various levels of irrigation (Table 9). In treatment IW/ET=1, crude protein content was 0.24 mg/g, in IW/ET=0.6, it was 0.21 mg/g and in IW/ET=0.3, crude protein content was measured as 0.22 mg/g.

Mahogany

Well irrigated treatments (IW/ET=1 and 0.6) showed higher amount of crude protein content (0.65 mg/g and 0.55 mg/g respectively) whereas in treatment IW/ET=0.3, a significant decrease in crude protein content (0.21 mg/g) was observed (Table 9). No significant difference was observed among treatments IW/ET=1 and 0.6 in response to different irrigation treatments.

4.2.3. Relative growth rate

Teak

Different levels of irrigation had significant effect on relative growth rate of teak seedlings (Table 10 and Figure 8). After 40 days, IW/ET=1 and 0.6 showed high rate of relative growth. Seedlings with irrigation at IW/ET=0.3 showed minimum RGR (0.001g g^{-1} day^{-1}) whereas IW/ET=1 showed maximum growth of 0.106 g g^{-1} day^{-1} which was on par with IW/ET=0.3 (0.103 g g^{-1} day^{-1}).

Table 9 Effect of different irrigation levels on crude protein content in seedlings after six months growth

Treatments	Crude protein content(mg/ml)	
	Teak	Mahogany
IW/ET=1	0.24	0.65^{a}
IW/ET=0.6	0.21	0.55^{a}
IW/ET=0.3	0.22	0.21^{b}
SEm$\pm$	0.2^{ns}	0.1*

* Significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

Table 10 Effect of different levels of irrigation on relative growth rate (g g^{-1} day^{-1}) of seedlings

Treatments	40 days (g g^{-1} day^{-1})		168 days (g g^{-1} day^{-1})	
	Teak	Mahogany	Teak	Mahogany
IW/ET=1	0.0299^{a}	0.0148^{a}	0.0106^{a}	0.0019^{a}
IW/ET=0.6	0.0247^{a}	0.0151^{a}	0.0103^{a}	0.0016^{a}
IW/ET=0.3	0.0171^{b}	0.0118^{b}	0.0010^{b}	0.0004^{b}
IW/ET=0	0.0100^{c}	0.0029^{c}	M	M
SEm$\pm$	0.0070*	0.0003*	0.009*	0.0005*

* Significant at 0.05 levels; Values with similar superscript along the column do not differ significantly; M- Observations could not complete due to mortality of seedlings

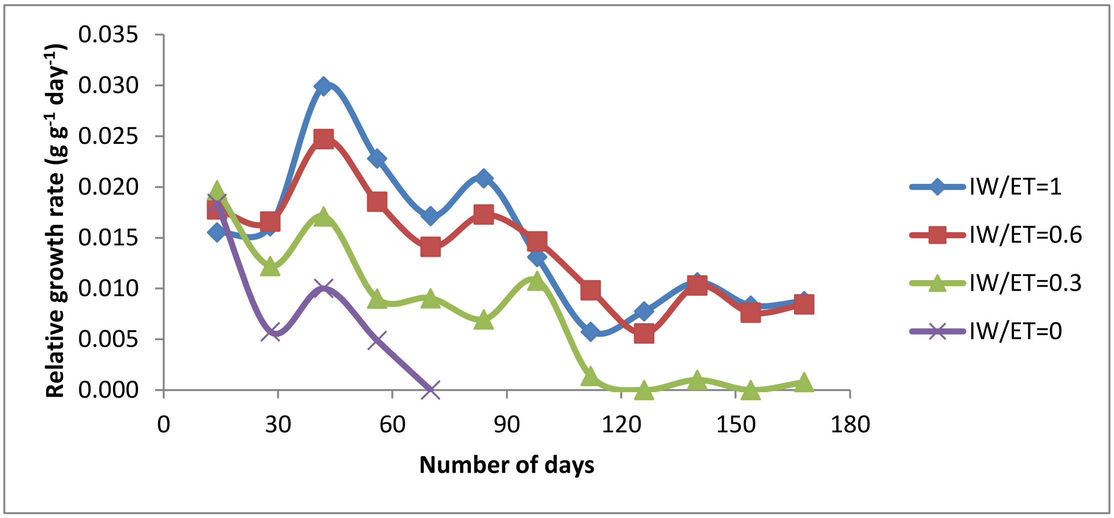

Figure 8 Effect of different levels of irrigation on relative growth rate (g g^{-1} day^{-1}) of teak seedlings

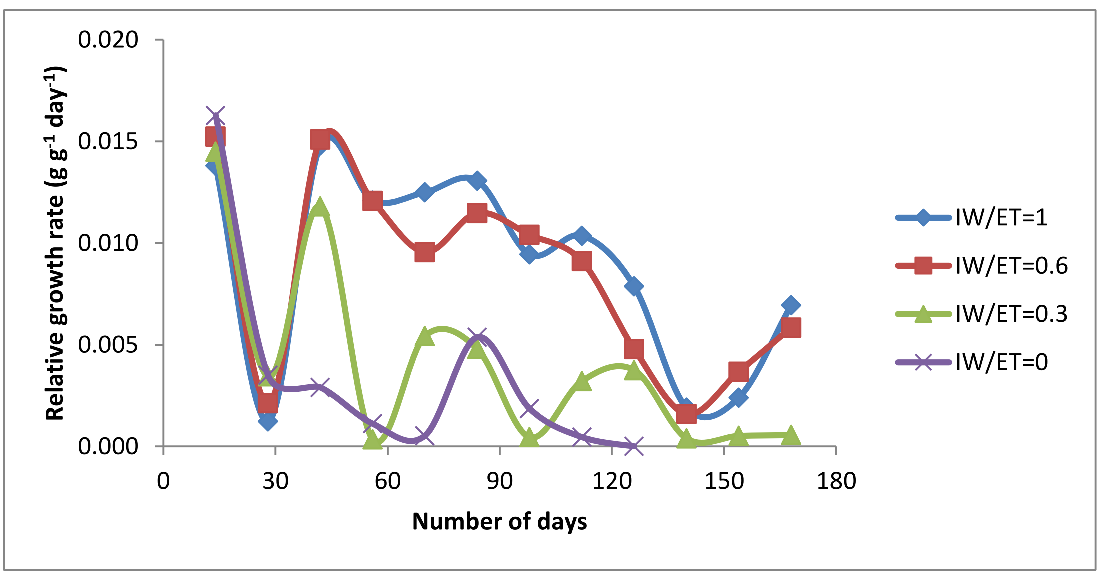

Figure 9 Effect of different levels of irrigation on relative growth rate (g g^{-1} day^{-1}) of mahogany seedlings

Mahogany

In mahogany, relaitive growth rate was more in well watered treatments (IW/ET=1 and 0.6) when compared to other two. Non watered IW/ET=0 seedlings showed minimum increase in growth followed by IW/ET=0.3. Pattern of relative growth rate has been illustrated in Table 10 and Figure 9).

4.2. Biometric observations

Observations on various growth parameters of seedlings were recorded at fortnightly intervals. It was taken from five randomly harvested seedlings of each treatment. Growth observations are discussed under these subheadings.

4.2.1. Height

Teak

Seedling height of teak grown under different irrigation regimes are given in Table 11 and Figure 10. No significant difference was observed in seedling height in the first and second fortnight intervals. Later IW/ET=0 and IW/ET=0.3 showed a significant reduction compared to other two treatments. Mortality of control seedlings occurred at the end of third month of observation. At that time well irrigated treatments (IW/ET=1 and 0.6) showed more height than treatment IW/ET=0 and IW/ET=0.3. During this period the mean height of seedlings in the well irrigated treatment was 85.9 cm (IW/ET=1) and 84.9 cm (IW/ET=0.6). Treatment IW/ET=0.3 showed a mean height of 69.9 cm where as IW/ET=0 showed 67.2 cm height. At the end of six months treatment IW/ET=1 and IW/ET=0.6 showed more height (110.1 cm and 107.1 cm respectively). Least irrigated seedlings of treatment IW/ET=0.3 exhibited minimum height (96.5 cm).

Mahogany

Mean performance of height of mahogany seedlings under different irrigation treatment are given in Table 12 and Figure 11. There was no significant difference in

Table 11 Height (cm) of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	49.0	52.1	62.9[a]	73.2[a]	79.8[a]	85.7[a]	88.2[a]	90.1[a]	94.1[a]	96.2[a]	99.3[a]	103.1[a]	110.1[a]
IW/ET=0.6	51.6	52.7	64.8[a]	77.1[a]	83.6[a]	84.9[a]	86.9[a]	89.3[a]	91.0[a]	94.0[a]	98.4[a]	100.5[a]	107.2[a]
IW/ET=0.3	54.4	55.4	58.9[b]	62.4[b]	66.9[b]	69.9[b]	74.3[b]	79.3[b]	82.5[b]	84.3[b]	87.5[b]	91.4[b]	96.5[b]
IW/ET=0	53.3	54.1	57.2[b]	61.2[b]	64.8[b]	67.2[b]	M	M	M	M	M	M	M
SEm$\pm$	4.4[ns]	3.8[ns]	3.9[*]	5.3[*]	4.9[*]	4.8[*]	5.4[*]	4.5[*]	4.9[*]	5.9[*]	5.4[*]	6.2[*]	5.1[*]

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

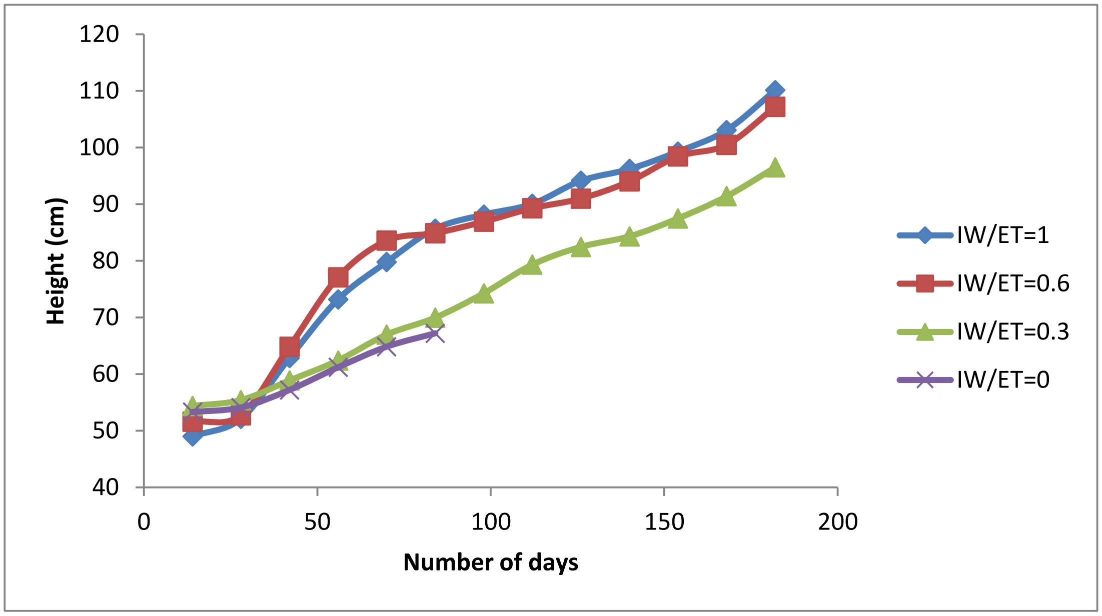

Figure 10 Height of teak seedlings as influenced by different irrigation levels

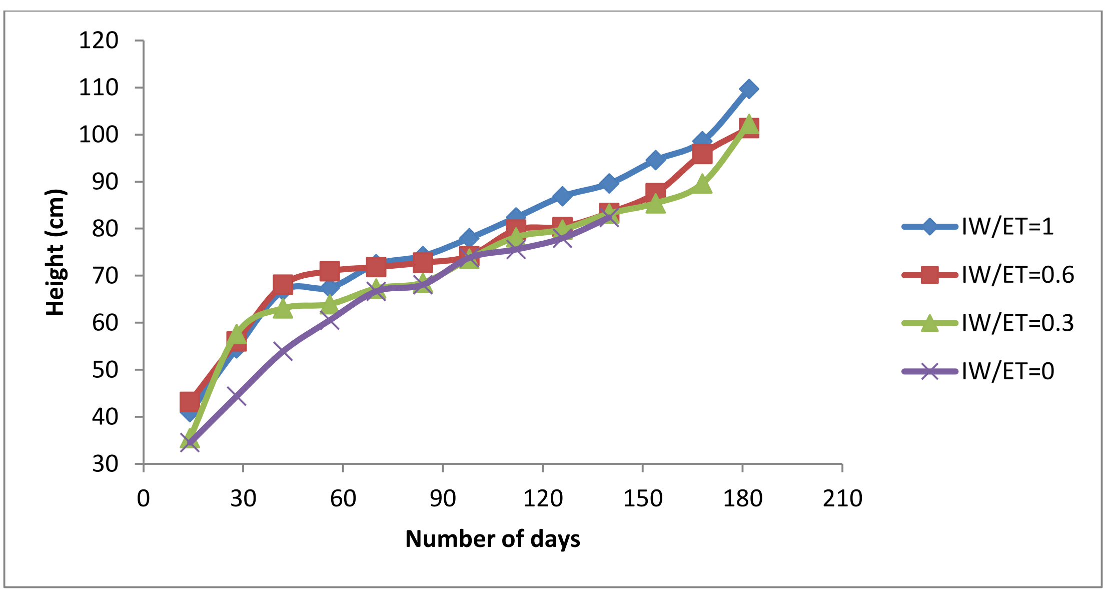

Figure 11 Height of mahogany seedlings as influenced by different irrigation levels

Table 12 Height (cm) of mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	41.0	54.6	66.9	67.5	72.5	74.2	78.0	82.4	86.9	89.6	94.0	98.6	109.7
IW/ET=0.6	43.2	56.1	68.1	71.0	71.9	72.8	74.2	79.8	80.4	83.4	87.6	95.9	101.4
IW/ET=0.3	35.5	57.6	63.1	63.9	67.3	68.5	73.6	78.2	79.8	83.2	85.4	89.6	102.3
IW/ET=0	34.5	44.4	53.9	60.6	66.7	68.1	73.8	75.6	78.1	82.4	M	M	M
SEm$\pm$	10.2^{ns}	16.7^{ns}	19.9^{ns}	15.4^{ns}	9.5^{ns}	7.7^{ns}	7.2^{ns}	8.5^{ns}	9.7^{ns}	8.6^{ns}	11.6^{ns}	15.9^{ns}	7.9^{ns}

ns- Non significant at 0.05 levels; M- Observations could not complete due to mortality of seedlings seedling height under various irrigation levels at any stages of growth. Mortality of seedlings in treatment IW/ET=0 occurred after 140 days of irrigation withdrawal. At the end of six months, treatment IW/ET=1 showed maximum height of 109.7 cm followed by IW/ET=0.3 (102.3cm) and IW/ET=0.6 (101.4 cm).

4.2.2. Collar diameter

Teak

After three months of irrigation treatments a significant difference in collar diameter was noticed among treatments in teak seedlings (Table 13 and Figure 12). A significant reduction in collar diameter of seedlings irrigated at lowest level (IW/ET=0.3) was observed and this trend continued till the end of six months. Collar diameter was more in treatment IW/ET=1 and 0.6 with no significant difference in between these two. At the end of six months treatment IW/ET=1 exhibited the maximum collar diameter (8.5 mm) followed by IW/ET=0.6 (7.7 mm) and IW/ET=0.3 (6.6 mm).

Mahogany

Mahogany seedlings showed significant difference in collar diameter due to different irrigation treatments (Table 14 and Figure 13). Least irrigated (IW/ET=0.3) and non irrigated (IW/ET=0) seedlings showed reduction in collar diameter till the end of experiment. These two treatments were on par with each other. No significant difference was observed between the well irrigated treatments (IW/ET=1 and 0.6). At the end of six months IW/ET=1 had a mean collar diameter of 10.9 mm. Treatment IW/ET=0.6 showed 10.4 mm and IW/ET=0.3 had a mean collar diameter of 8.3 mm. Compared to teak seedlings of same age and treatments, mahogany seedlings showed a better performance in terms of collar diameter.

a. Teak seedlings grown under different irrigation regimes

b. Mahogany seedlings grown under different irrigation regimes

Plate 5. Height of seedlings grown under different irrigation regimes

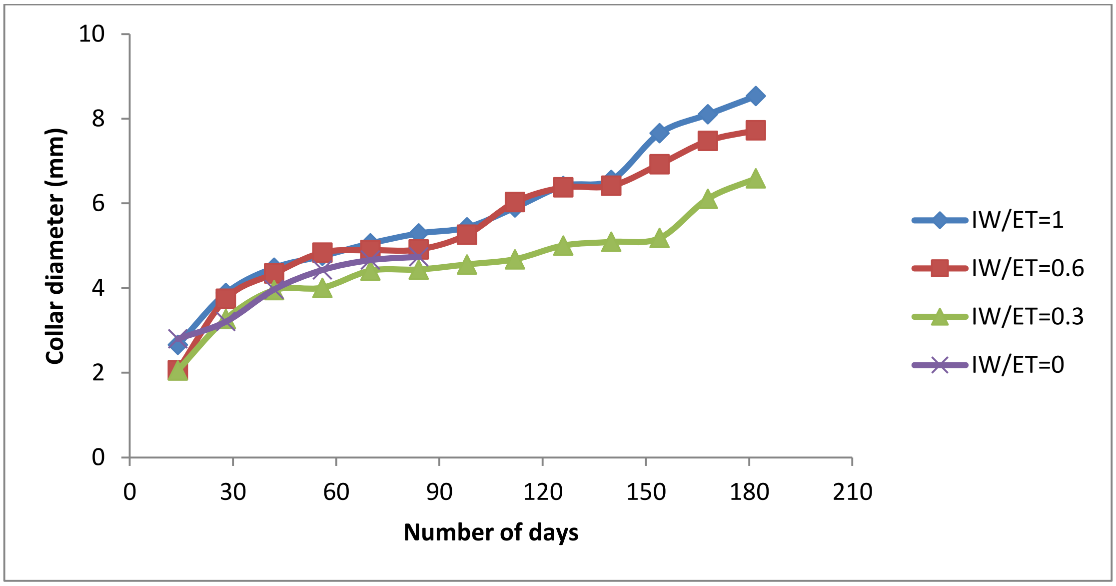

Figure 12 Collar diameter of teak seedlings as influenced by different irrigation levels

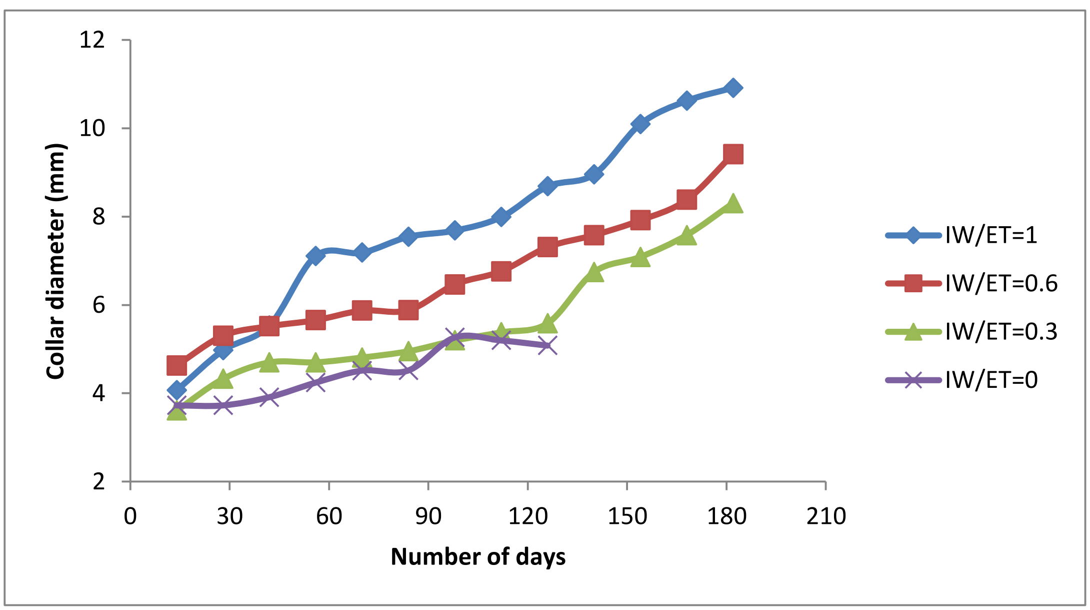

Figure 13 Collar diameter of mahogany seedlings grown under different irrigation regimes

Table 13 Collar diameter (mm) of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	2.7	3.9	4.5	4.8	5.1	5.3	5.4	5.9^{a}	6.4^{a}	6.6^{a}	7.7^{a}	8.1^{a}	8.5^{a}
IW/ET=0.6	2.1	3.8	4.4	4.8	4.9	4.9	5.3	6.0^{a}	6.4^{a}	6.4^{a}	6.9^{ab}	7.5^{ab}	7.7^{a}
IW/ET=0.3	2.1	3.3	3.9	4.0	4.4	4.4	4.6	4.7^{b}	5.0^{b}	5.1^{b}	5.2^{b}	6.1^{b}	6.6^{b}
IW/ET=0	2.8	3.2	3.9	4.4	4.7	4.7	M	M	M	M	M	M	M
SEm$\pm$	0.9^{ns}	0.9^{ns}	0.8^{ns}	0.9^{ns}	0.8^{ns}	1.2^{ns}	1.1^{ns}	0.5^{*}	0.6^{*}	0.5^{*}	1.7^{*}	1.4^{*}	0.9^{*}

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

Table 14 Collar diameter (mm) of mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	4.1	4.9^{a}	5.5^{a}	6.1^{a}	7.2^{a}	7.5^{a}	7.7^{a}	7.9^{a}	8.7^{a}	8.9^{a}	10.1^{a}	10.6^{a}	10.9^{a}
IW/ET=0.6	4.7	5.3^{a}	5.5^{a}	5.7^{a}	5.9^{b}	5.9^{b}	6.5^{a}	6.8^{a}	7.3^{a}	8.6^{a}	9.9^{a}	10.4^{a}	10.4^{a}
IW/ET=0.3	3.6	4.3^{ab}	4.7^{ab}	4.7^{b}	4.8^{b}	4.9^{b}	5.2^{b}	5.4^{b}	5.6^{b}	6.7^{b}	7.1^{b}	7.6^{b}	8.3^{b}
IW/ET=0	3.7	3.8^{b}	3.9^{b}	4.2^{b}	4.5^{b}	4.5^{b}	5.1^{b}	5.2^{b}	5.3^{b}	M	M	M	M
SEm$\pm$	1.3^{ns}	0.6^{*}	0.8^{*}	1.7^{*}	1.4^{*}	1.4^{*}	1.4^{*}	1.6*	1.9^{*}	0.9^{*}	1.0^{*}	0.6^{*}	0.7^{*}

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

4.2.3. Number of leaves

Teak

Number of leaves produced in teak seedlings under different levels of irrigation varied significantly (Table 15 and Figure 20). Severely water stressed teak seedlings (IW/ET=0 and IW/ET=0.3) showed a significant reduction in number of leaves from the second fortnight of treatment. Number of leaves in seedlings of other two treatments (irrigation at IW/ET=1 and irrigation at IW/ET=0.6) was high and showed no significant variation among each other most of the time. Performance of IW/ET=0 and IW/ET=0.3 in terms of number of leaves were on par. Total number of leaves in IW/ET=1, IW/ET=0.6 and IW/ET=0.3 were 12.6, 12.2 and 9.3 respectively at the end of six month period.

Mahogany

There was no significant difference on the number of leaflets produced by mahogany due to the effect of various levels of irrigation treatments (Table 16 and Figure 21). But the numerical maximum obtained was 14.4 for IW/ET=0.6, followed by 14 (IW/ET=1) and 13.6 (IW/ET=0.3)

4.2.4. Shoot weight

Teak

Observations on shoot weight of teak seedlings is given in Table 17 and illustrated in Figure 16. Change in shoot weight was not significant among the treatments during the first two month in teak seedlings. Later on seedlings in IW/ET=0 showed significant reduction in shoot weight, whereas no difference was observed among other three treatments. After 18 weeks of irrigation at IW/ET=0.3 exhibited significant decline in shoot weight was noticed which continued upto the end of the experiment. No difference was observed between the other two treatments (irrigation

Table 15 Number of leaves of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	7.2	7.6[a]	8.4[a]	8.6[a]	9.8[a]	10.0[a]	10.4[a]	10.6[a]	11.0[a]	11.5[a]	12.0[a]	12.2[a]	12.6[a]
IW/ET=0.6	6.7	8.0[a]	8.2[a]	8.6[a]	8.7[a]	9.2[a]	9.6[a]	9.7[a]	9.8[b]	10.4[b]	11.6[a]	12.0[a]	12.2[a]
IW/ET=0.3	6.8	6.9[b]	7.3[b]	7.4[b]	7.5[b]	7.6[b]	7.7[b]	7.8[b]	7.9[c]	8.0[c]	8.3[b]	8.4[b]	9.3[b]
IW/ET=0	6.7	6.8[b]	7.1[b]	7.3[b]	7.4[b]	7.5[b]	M	M	M	M	M	M	M
SEm±	1.3[ns]	0.5*	1.0*	1.2*	1.2*	1.6*	1.6*	1.7*	1.7*	1.0*	1.4*	1.6*	1.5*

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

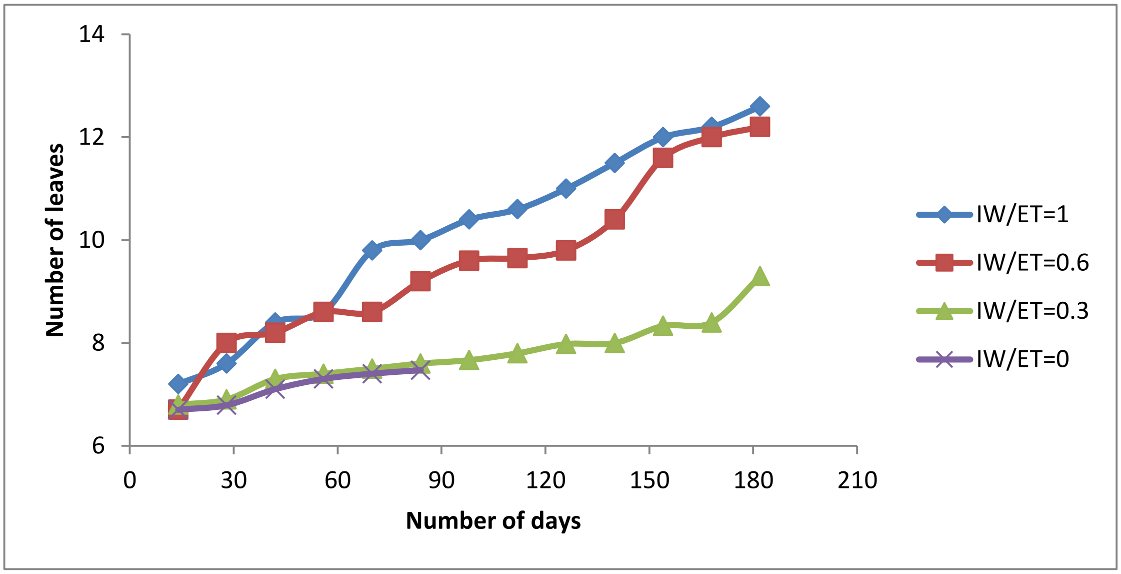

Figure 14 Number of leaves of teak seedlings as influenced by different irrigation levels

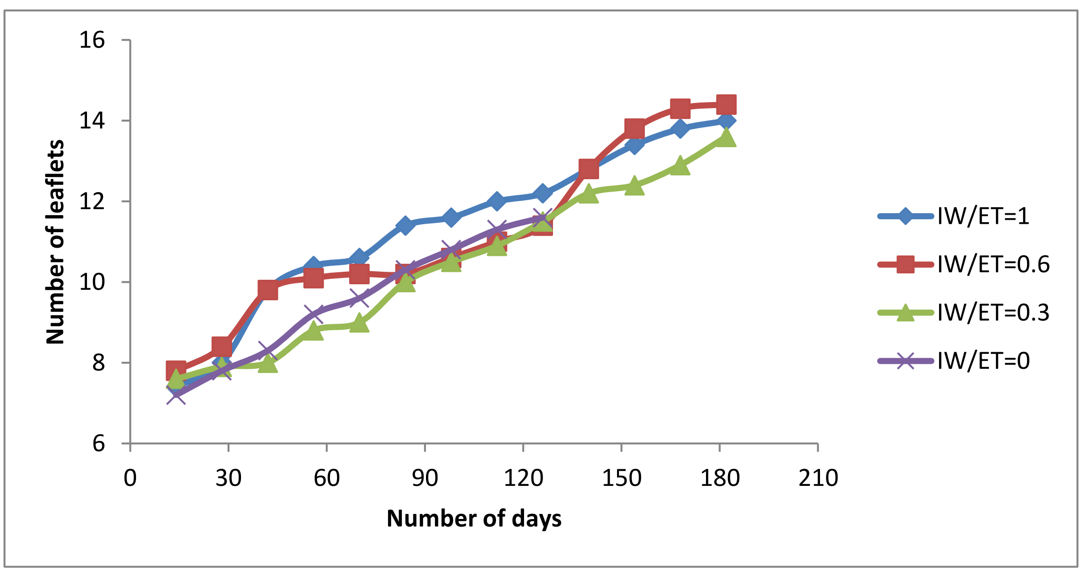

Figure 15 Number of leaflets of mahogany seedlings grown under different irrigation regimes

Table 16 Number of leaflets in mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	7.4	8.0	9.8	10.4	10.6	11.4	11.6	12.0	12.2	12.8	13.4	13.8	14
IW/ET=0.6	7.8	8.4	9.8	10.1	10.2	10.2	10.6	11.0	11.4	12.8	13.8	14.3	14.4
IW/ET=0.3	7.6	7.9	8.0	8.8	9.0	10.0	10.5	10.9	11.5	12.2	12.4	12.9	13.6
IW/ET=0	7.2	7.8	8.3	9.2	9.6	10.3	10.8	11.3	11.6	M	M	M	M
SEm$\pm$	1.9^{ns}	2.3^{ns}	2.1^{ns}	2.1^{ns}	2.3^{ns}	2.4^{ns}	2.1^{ns}	2.3^{ns}	2.5^{ns}	2.2^{ns}	2.5^{ns}	2.6^{ns}	2.6^{ns}

ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

Table 17 Shoot weight (g) of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	2.3	2.9	3.2	3.3	3.5[a]	4.9[a]	5.1[a]	5.4[a]	5.9[a]	6.4[a]	7.1[a]	7.9[a]	8.7[a]
IW/ET=0.6	2.7	2.9	3.5	3.7	3.8[a]	4.5[a]	4.9[a]	4.9[a]	5.6[a]	5.9[a]	6.6[a]	7.2[a]	7.9[a]
IW/ET=0.3	1.4	2.2	2.7	3.1	3.5[a]	4.1[a]	4.4[b]	4.2[b]	5.0[b]	5.4[b]	5.9[b]	5.9[b]	6.4[b]
IW/ET=0	1.6	2.0	2.6	2.8	3.0[b]	3.4[b]	M	M	M	M	M	M	M
SEm±	1.4[ns]	1.1[ns]	1.1[ns]	1.0[ns]	0.4*	0.6*	0.4*	0.6*	0.4*	0.7*	0.6*	1.1*	1.2*

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

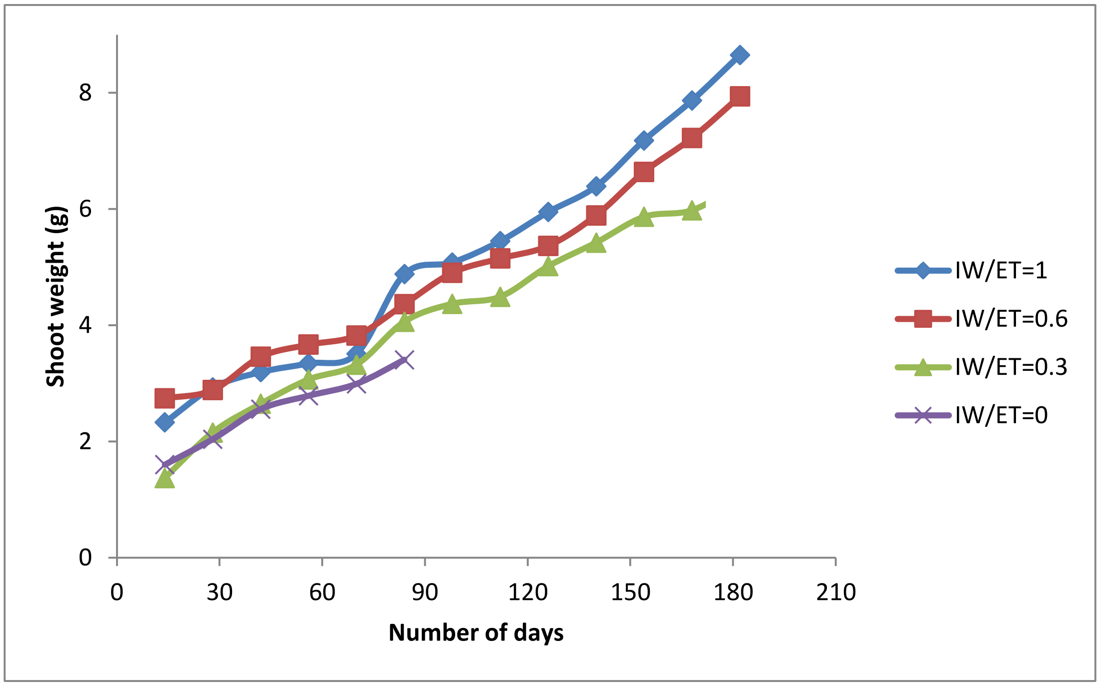

Figure 16 Shoot weight of teak seedlings as influenced by different irrigation levels

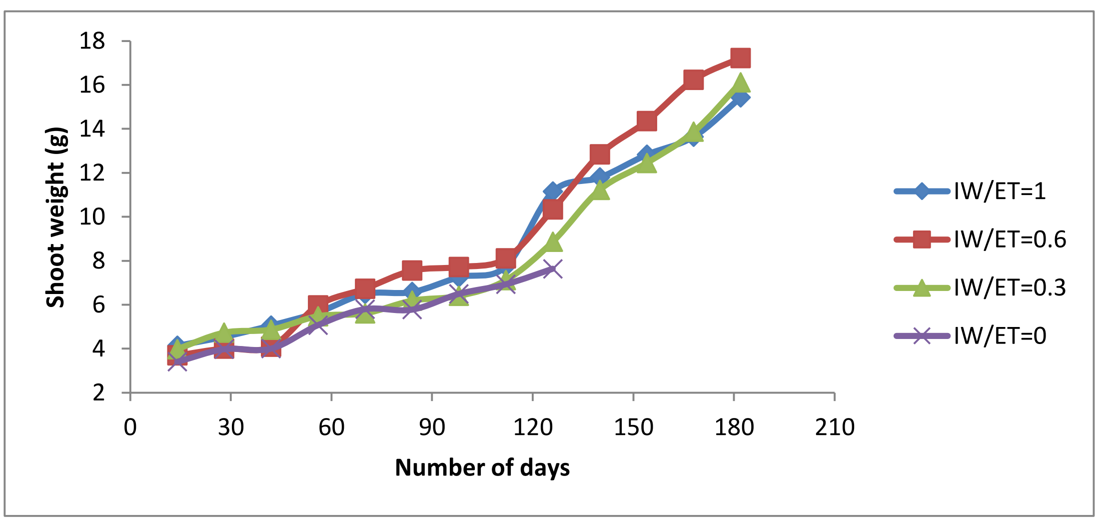

Figure 17 Effect of different levels of irrigation on shoot weight of mahogany seedlings

Table 18 Shoot weight (g) of mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	4.1	4.5	5.1	5.7	6.5[a]	6.6[a]	7.3[a]	7.8[a]	11.2[a]	11.8	12.8	13.7	15.4
IW/ET=0.6	3.7	4.0	4.1	5.9	6.7[a]	6.7[a]	7.7[a]	8.1[a]	10.3[a]	12.8	14.3	16.2	17.2
IW/ET=0.3	3.9	4.7	4.9	5.5	5.6[b]	6.2[b]	6.4[b]	7.1[b]	8.9[b]	11.2	12.5	13.9	16.1
IW/ET=0	3.4	3.9	4.0	5.1	5.8[b]	5.9[b]	6.5[b]	6.9[b]	7.6[b]	M	M	M	M
SEm$\pm$	1.1[ns]	1.2[ns]	1.3[ns]	1.5[ns]	0.6*	0.4*	0.7*	0.6*	1.3*	2.1[ns]	2.3[ns]	4.5[ns]	2.6[ns]

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

at IW/ET=1 and 0.6). At the end of six months of irrigation treatment, seedlings of IW/ET=1 showed maximum shoot weight of 8.7 g, followed by IW/ET=0.6 (7.9 g). Seedlings of IW/ET=0.3 showed least shoot weight (6.4 g).

Mahogany

Shoot weight of mahogany seedlings is given in Table 18 and Figure 17. All the four treatments were on par in the first two months in terms of shoot weight. Later on treatments IW/ET=0.3 and IW/ET=0 showed a significant reduction in shoot weight. Other two treatments (IW/ET=1 and 0.6) were on par with each other. From 140 days onwards, the three remaining treatments did not show any difference among themselves. The values being 15.4g, 17.2g and 16.1g respectively for treatments IW/ET=1, IW/ET=0.6 and IW/ET=0.3 at the end of six months.

4.2.3. Root length

Teak

Root length of teak seedlings up to six weeks of irrigation treatment were not significantly different (Table 19 and Figure 18). Later on treatment IW/ET=0 started showing a significant increase in root length over the other three treatments. This pattern continued till the time of mortality of control seedlings. At the end of six month treatment with irrigation at IW/ET=0.3 showed maximum root length (63.9 cm). No significant difference between other two treatments IW/ET=1 (45.7 cm) and 0.6 (46.3 cm) was observed in the case of root length.

Mahogany

Response of root length of mahogany seedlings at various stages of growth is given in Table 20 and Figure 19. No significant difference was observed among root length among various treatments upto ten weeks after initiation of treatments. After that treatment IW/ET=0 followed by IW/ET=0.3 showed an increase in root

Table 19 Root length (cm) of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	26.9	34.3	35.7	37.3	39.8[b]	37.5[b]	38.6[b]	39.2[b]	42.7[b]	44.2[b]	44.7[b]	45.3[b]	45.7[b]
IW/ET=0.6	25.8	32.2	34.9	36.2	36.3[b]	37.3[b]	37.6[b]	40.3[b]	41.4[b]	43.5[b]	43.8[b]	45.2[b]	46.3[b]
IW/ET=0.3	26.8	29.0	33.2	37.7	39.5[b]	44.4[ab]	47.0[a]	49.2[a]	52.8[a]	54.5[a]	57.0[a]	59.6[a]	63.9[a]
IW/ET=0	24.4	35.7	37.8	39.9	43.6[a]	46.5[a]	M	M	M	M	M	M	M
SEm$\pm$	2.9[ns]	6.8[ns]	4.9[ns]	3.9[ns]	3.7*	2.1*	3.9*	4.2*	4.6*	4.9*	4.5*	4.5*	4.0*

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

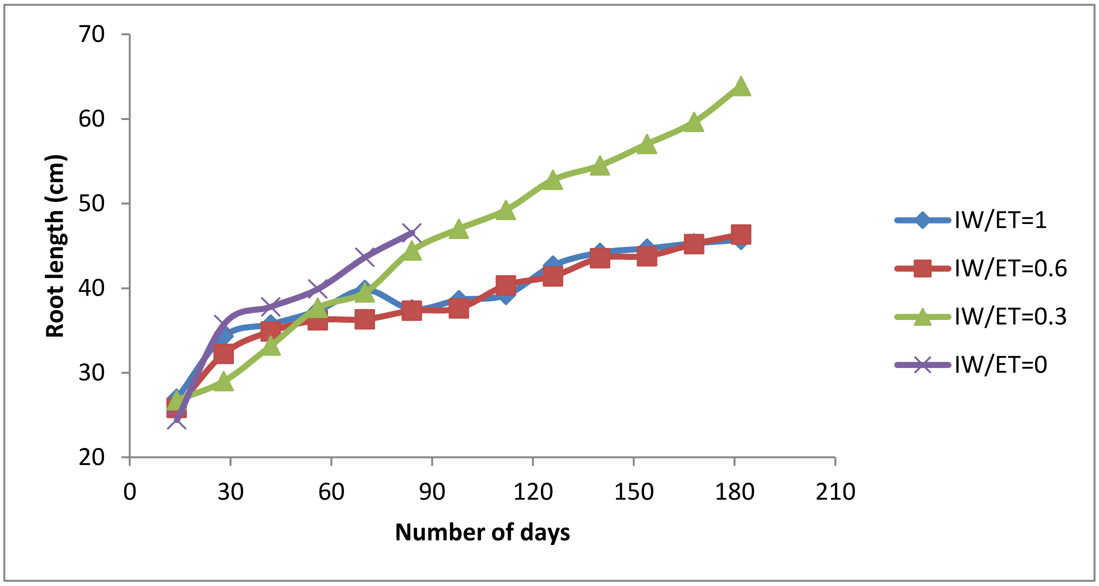

Figure 18 Effect of different levels of irrigation on root length of teak seedlings

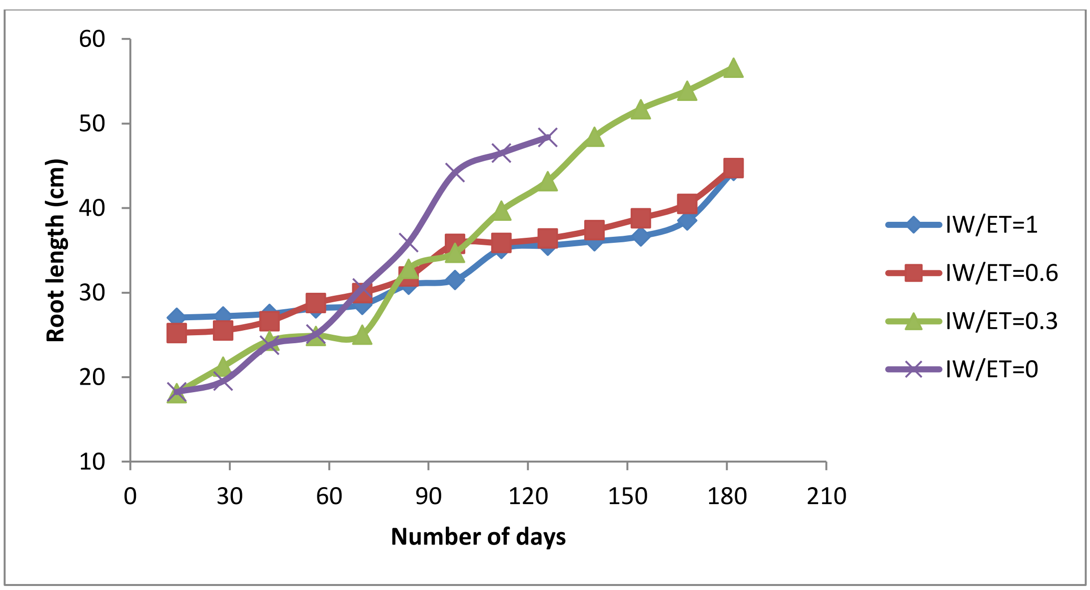

Figure 19 Effect of different levels of irrigation on root length of mahogany seedlings

Table 20 Root length (cm) of mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	26.0	27.2	27.5	28.1	28.6	30.9[b]	32.5[b]	35.2[b]	35.6[b]	36.1[b]	36.7[b]	38.6[b]	44.4[b]
IW/ET=0.6	25.2	25.5	26.6	28.8	29.9	31.9[b]	35.8[b]	35.9[b]	36.4[b]	37.4[b]	38.8[b]	40.5[b]	44.7[b]
IW/ET=0.3	24.6	26.3	27.3	29.9	30.0	32.8[b]	34.7[b]	39.7[b]	43.2[ab]	48.4[a]	51.7[a]	53.9[a]	56.6[a]
IW/ET=0	26.3	27.5	27.8	29.1	30.5	35.9[a]	39.2[a]	44.5[a]	48.4[a]	M	M	M	M
SEm$\pm$	3.5[ns]	3.1[ns]	2.7[ns]	3.4[ns]	3.6[ns]	3.5*	3.7*	4.7*	5.2*	4.2*	4.6*	4.3*	4.9*

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

length. At the end of six months the performance of seedlings with irrigation at IW/ET=0.3 was maximum with root length 56.6 cm. Well irrigated treatments showed lesser root length. No significant difference was observed between treatments IW/ET=1 (44.4 cm) and 0.6 (44.7 cm) in terms of root length.

4.2.3. Root weight

Teak

A significant reduction in root weight was observed in teak seedlings in treatment IW/ET=0.3 and IW/ET=0 from the eighth week of observation (Table 21 and Figure 20). This trend continued up to the end. No significant difference was observed among well watered treatments (IW/ET=1 and 0.6). After six months of irrigation treatment IW/ET=1 showed maximum root weight of 17.3 g followed by IW/ET= 0.6 having 16.6 g. However, they did not differ statistically. The minimum root weight was shown by IW/ET=0.3 (13.2 g).

Mahogany

No significant difference in root weight was observed among seedlings of mahogany under different levels of irrigation. The observations on root weight of mahogany seedlings under different treatment are given in Table 22 and Figure 21. At the end of the study period the root weight were 16.6g, 14.9g and 18.5g for treatments IW/ET=1, IW/ET=0.6 and IW/ET=0.3 respectively.

4.2.3. Shoot-root length ratio

Teak

Shoot-root length ratio exhibited significant variation among treatments with different levels of irrigation (Table 23 and Figure 22). Performance of IW/ET=0 seedlings was inferior throughout the experimental period. No significant difference

Table 21 Root weight (g) of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	5.4	6.2	6.8	9.4^{a}	10.4^{a}	11.9^{a}	12.9^{a}	13.2^{a}	14.8^{a}	15.4^{a}	16.3^{a}	17.1^{a}	17.3^{a}
IW/ET=0.6	4.8	7.3	7.3	8.4^{a}	7.6^{ab}	9.6^{ab}	11.6^{a}	12.4^{a}	13.6^{a}	13.8^{a}	15.4^{a}	15.8^{a}	16.6^{a}
IW/ET=0.3	3.4	4.9	5.9	6.3^{b}	6.9^{b}	7.2^{b}	7.4^{b}	7.6^{b}	9.1^{b}	9.6^{b}	9.9^{b}	11.2^{b}	13.2^{b}
IW/ET=0	4.0	4.8	5.8	6.5^{b}	6.7^{b}	7.3^{b}	M	M	M	M	M	M	M
SEm$\pm$	2.4^{ns}	2.9^{ns}	2.7^{ns}	2.0^{*}	0.9^{*}	2.4^{*}	4.1^{*}	4.5^{*}	4.3^{*}	4.1^{*}	4.2^{*}	2.6^{*}	2.7^{*}

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

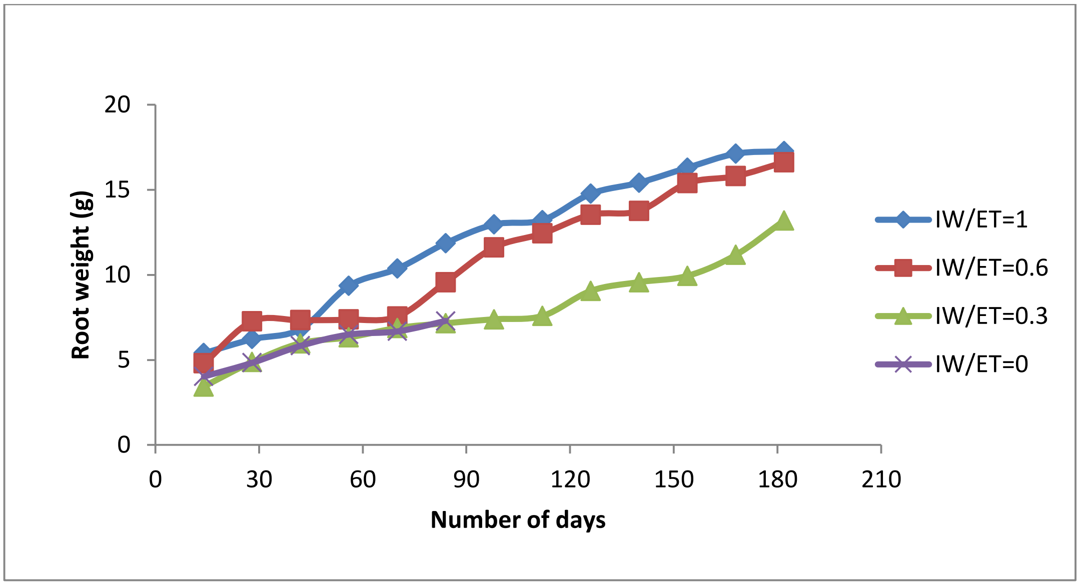

Figure 20 Effect of different levels of irrigation on root weight of teak seedlings

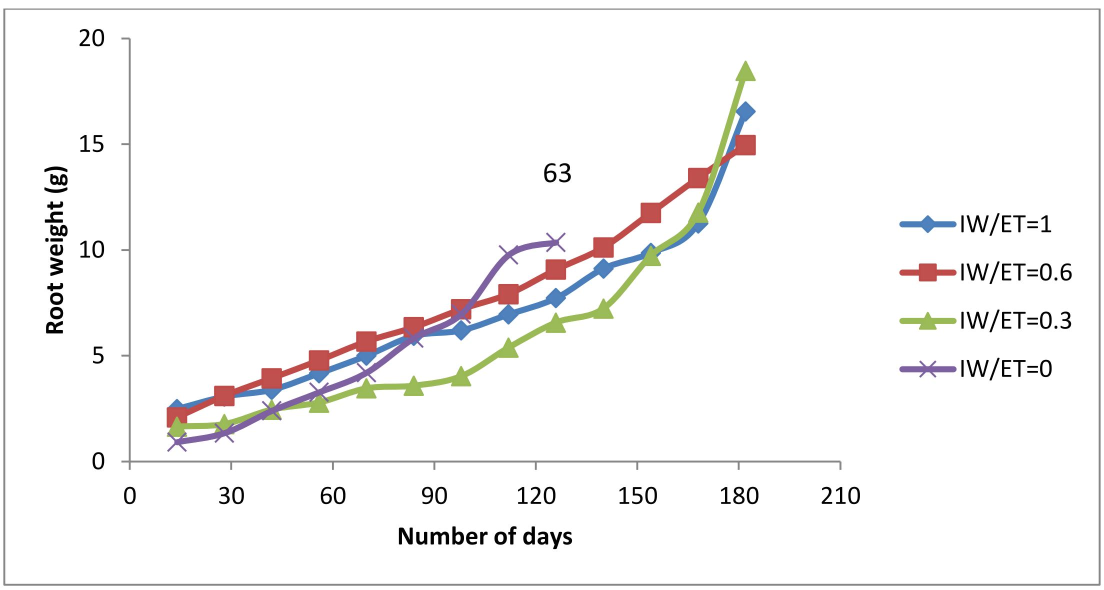

Figure 21 Effect of different levels of irrigation on root weight of mahogany seedlings

Table 22 Root weight (g) of mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	2.4	3.1	3.4	4.2	4.9	5.9	6.2	6.9	7.7	9.1	9.9	11.3	16.6
IW/ET=0.6	2.1	3.1	3.9	4.8	5.7	6.3	7.2	7.9	9.1	10.1	11.8	13.4	14.9
IW/ET=0.3	1.6	1.8	2.5	2.8	3.5	3.6	4.0	5.4	6.6	7.2	9.7	11.8	18.5
IW/ET=0	0.9	1.3	2.4	3.3	4.2	5.8	6.9	9.8	10.4	M	M	M	M
SEm$\pm$	1.3^{ns}	1.9^{ns}	1.8^{ns}	2.3^{ns}	2.5^{ns}	2.9^{ns}	3.7^{ns}	4.5^{ns}	3.9^{ns}	3.1^{ns}	2.5^{ns}	2.2^{ns}	3.7^{ns}

ns- Non significant at 0.05 levels; Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

was observed among the other treatments in terms of shoot-root length ratio up to two months. Later IW/ET=0.3 showed a decrease over other two well watered treatments (IW/ET=1 and 0.6). Minimum ratio obtained is 0.5 from IW/ET=0.3 at the end of six months. Treatment IW/ET=1 and 0.6 were on par with each other.

Mahogany

Performance of mahogany seedlings provided with different irrigation regimes in terms of shoot-root length ratio is illustrated in Table 24 and Figure 23. No significant difference was observed in shoot-root length ratio between different treatments upto 140 days of observation. At the end of six months lowest shoot-root length ratio was recorded from treatment IW/ET=0.3 (0.8). Other two treatments IW/ET=1 and 0.6 which were on par.

4.2.3. Shoot-root biomass ratio

Teak

A significant reduction was observed in shoot-root biomass ratio of seedlings in treatment IW/ET=0 (Table 25 and Figure 24). No significant difference among the remaining treatments with respect to shoot-root biomass ratio was observed in teak.

Mahogany

The results with respect to this character have been tabulated and explained (Table 26 and Figure 25). All treatments responded similarly under different levels of irrigation in terms of shoot-root biomass ratio. It was 0.9 for IW/ET=1 and 1 for treatments IW/ET=0.6 and 0.3.

Table 23 Shoot-root length ratio of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	0.8	0.5	0.8	1.0	1.0^{ba}	1.3^{a}	1.3^{a}	1.3^{a}	1.2^{a}	1.2^{a}	1.2^{a}	1.3^{a}	1.4^{a}
IW/ET=0.6	1.0	0.6	0.9	1.1	1.3^{a}	1.3^{a}	1.3^{a}	1.2^{a}	1.2^{a}	1.2^{a}	1.2^{a}	1.2^{a}	1.3^{a}
IW/ET=0.3	1.0	0.9	0.8	0.7	0.7^{ab}	0.6^{ab}	0.6^{ab}	0.6^{b}	0.6^{b}	0.5^{b}	0.5^{b}	0.5^{b}	0.5^{b}
IW/ET=0	1.2	0.5	0.5	0.5	0.5^{b}	0.4^{b}	M	M	M	M	M	M	M
SEm±	2.5^{ns}	3.3^{ns}	2.5^{ns}	0.8^{ns}	1.4^{*}	1.7^{*}	1.3^{*}	1.4^{*}	1.7^{*}	1.3^{*}	1.4^{*}	1.4^{*}	1.3^{*}

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

Table 24 Shoot-root length ratio of mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	0.6	1.0	1.4	1.4	1.5	1.4	1.5	1.3	1.4	1.5^{a}	1.6^{a}	1.6^{a}	1.5^{a}
IW/ET=0.6	0.7	1.2	1.6	1.5	1.4	1.3	1.1	1.2	1.2	1.2^{a}	1.3^{a}	1.4^{a}	1.3^{a}
IW/ET=0.3	0.4	1.2	1.3	1.1	1.2	1.1	1.1	1.0	0.8	0.7^{b}	0.7^{b}	0.7^{b}	0.8^{b}
IW/ET=0	0.3	0.6	0.9	1.1	1.2	0.9	0.9	0.7	0.6	M	M	M	M
SEm$\pm$	1.3^{ns}	5.0^{ns}	1.7^{ns}	2.5^{ns}	2.0^{ns}	1.4^{ns}	1.4^{ns}	1.3^{ns}	1.1^{ns}	2.0^{*}	1.7^{*}	1.3^{*}	1.7^{*}

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

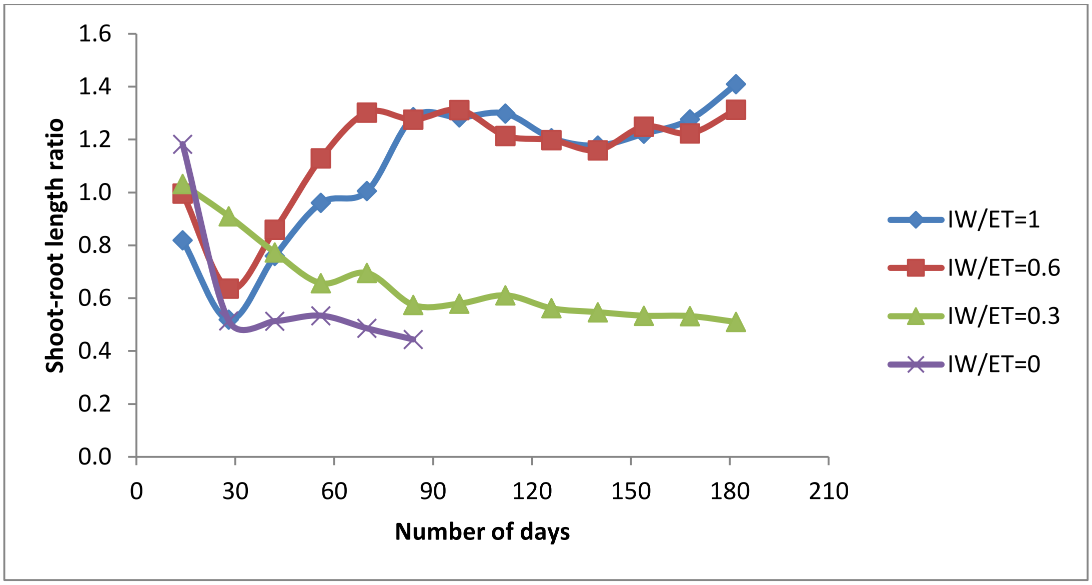

Figure 22 Effect of different levels of irrigation on shoot-root length ratio of teak seedlings

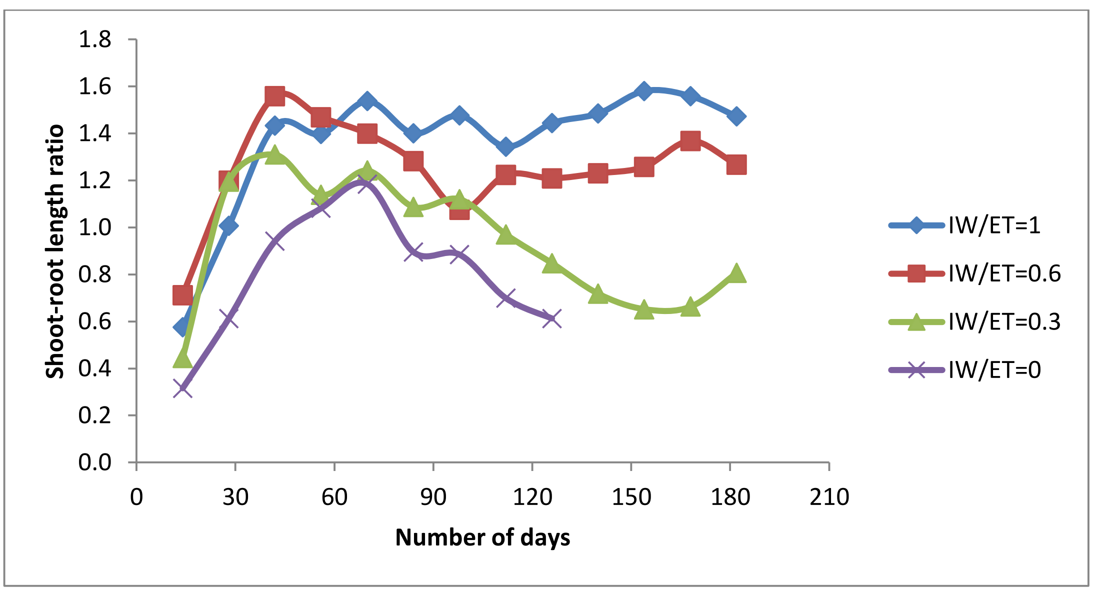

Figure 23 Effect of different levels of irrigation on shoot-root length ratio of mahogany seedlings

Table 25 Shoot-root biomass ratio of teak seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	0.5	0.3	0.5	0.7^{a}	0.4^{b}	0.4^{a}	0.5	0.8	0.5	0.9	0.8	0.7	0.8
IW/ET=0.6	0.5	0.6	0.6	0.6^{ab}	0.5^{ab}	0.4^{a}	0.6	0.8	0.8	0.7	0.8	0.7	0.8
IW/ET=0.3	0.5	0.8	0.7	0.6^{ab}	0.7^{a}	0.3^{ab}	0.8	0.8	0.9	1.0	1.0	1.2	1.2
IW/ET=0	0.6	0.5	0.4	0.5^{b}	0.5^{ab}	0.2^{b}	M	M	M	M	M	M	M
SEm±	0.3^{ns}	0.7^{ns}	0.5^{ns}	0.1^{*}	0.2^{*}	0.1^{*}	0.4^{ns}	0.4^{ns}	0.5^{ns}	0.6^{ns}	0.3^{ns}	0.7^{ns}	0.8^{ns}

* Significant at 0.05 levels; ns- non significant at 0.05 levels

Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

Table 26 Shoot-root biomass ratio of mahogany seedlings under different irrigation levels

Treatments	Number of days												
	14	28	42	56	70	84	98	112	126	140	154	168	182
IW/ET=1	0.5	1.4	1.6	2.2	1.7	1.9	1.3	1.1	1.4	1.7	0.6	0.7	0.9
IW/ET=0.6	0.4	1.1	2.1	1.7	2.7	2.8	1.5	1.6	1.3	1.3	0.6	0.8	1.0
IW/ET=0.3	0.6	1.7	2.1	2.0	2.0	2.0	1.5	1.3	1.1	1.1	0.6	0.8	1.0
IW/ET=0	0.6	1.9	1.5	1.2	1.7	2.7	1.6	1.6	1.0	M	M	M	M
SEm±	0.5^{ns}	0.9^{ns}	0.7^{ns}	1.1^{ns}	1.2^{ns}	1.1^{ns}	0.7^{ns}	0.4^{ns}	0.7^{ns}	0.7^{ns}	0.1^{ns}	0.3^{ns}	0.5^{ns}

ns- Non significant at 0.05 levels; Values with similar superscript along the column do not differ significantly

M- Observations could not complete due to mortality of seedlings

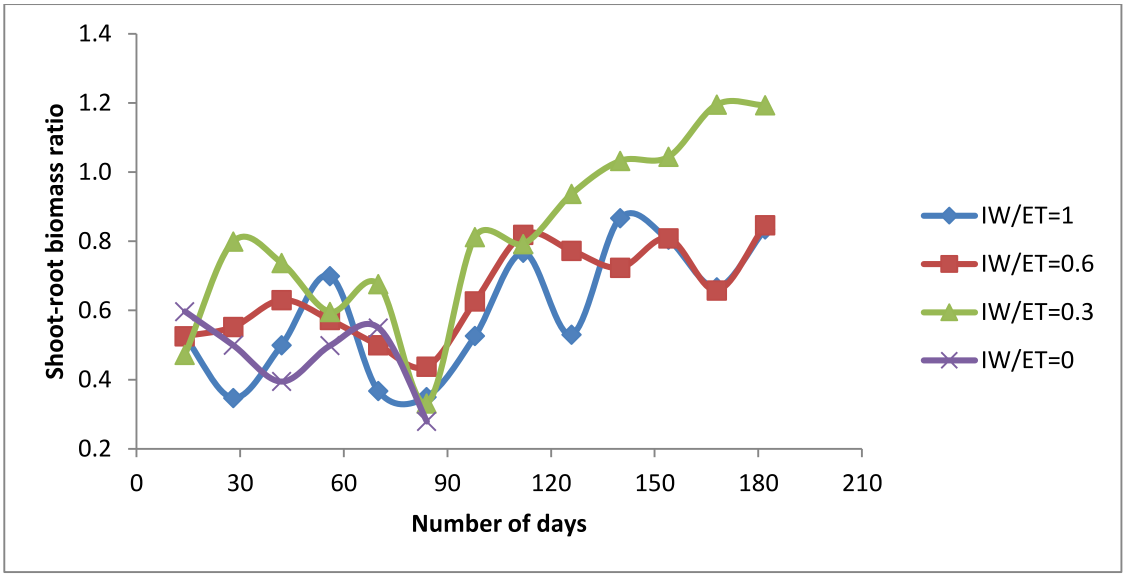

Figure 24 Effect of different levels of irrigation on shoot-root biomass ratio of teak seedlings

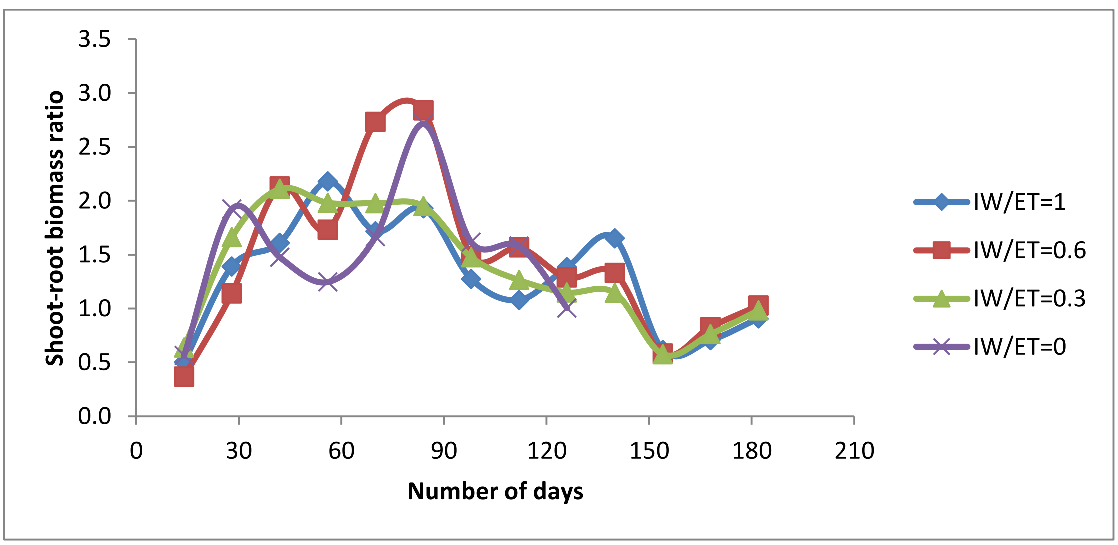

Figure 25 Effect of different levels of irrigation on shoot-root biomass ratio of mahogany seedlings

DISCUSSION

DISCUSSION

The results of the experiment revealed that the different levels of irrigation have influenced physiological parameters as well as biometric parameters of teak and mahogany seedlings.

5.1. Physiological parameters

5.1.1. Canopy air temperature difference (CATD) (˚C)

From the observations it was found that CATD of teak seedlings from well watered treatments (IW/ET=1 and 0.6) remained negative during the time of observation which indicate seedlings from both treatments have not experienced any water stress. But for treatment IW/ET=0.3 and IW/ET=0, CATD was positive and were under water stress throughout the growing period. There was no significant difference between CATD of treatments IW/ET=1 and 0.6. Even if we provide more water, the plants may not show a corresponding increase in the rate of transpiration. CATD of IW/ET=0.3 remained positive. The amount of water provided in this treatment (IW/ET=0.3) may not be sufficient to meet the water requirement of the plants to provide evaporative cooling. Even though the difference in CATD within the treatment was not significant, there was increase in CATD towards the end of a week was observed which might be due to depletion of soil moisture as a result of evapotranspiration. In IW/ET=1 and 0.6 maximum value obtained in the next day after irrigation. This suggests that plants may take some time to make use of irrigated water and in case of teak; seedlings took almost one day for alliviating from the stress.

For mahogany, CATD of IW/ET=0 and IW/ET=0.3 were positive whereas for well watered treatments (IW/ET=1 and 0.6), it remained negative. This implies that IW/ET=0 and IW/ET=0.3 were under water stress throughout the entire growing period whereas treatments IW/ET=1 and 0.6 were not. Irrigation at levels IW/ET=1 and 0.6 were sufficient to meet the evaporative demand. No significant difference was observed among mahogany seedlings in the treatments IW/ET=1 and 0.6 in terms of CATD, which implies that IW/ET=0.6 is enough for the plants to maintain normal canopy temperature. Performance of seedlings in treatment IW/ET=0.3 was found to be lower than that of IW/ET=0 up to sixth day but increased and remained on par with IW/ET=0 on seventh day. This increase in CATD might be due to complete depletion of soil water on seventh day after irrigation. CATD of treatment IW/ET=1 and IW/ET=0 remained without any significant difference all over the week. In IW/ET=1 no significant variation was observed in CATD may be due to availability of sufficient amount of water at all the time, but in treatment IW/ET=0 plants maintained almost steady CATD might be due to ability of plants to acclimate with water stress. Significant increase in CATD of IW/ET=0.6 and IW/ET=0.3 might be due to soil water depletion and reduced evapotranspiration on course of time after irrigation.

5.1.2. Development of baseline equations for canopy air temperature difference (CATD)

For teak the lower baseline was determined as CATD = -1.01VPD+2.8 which represents relation between CATD and VPD for maximum transpiration of non water stressed seedlings. The upper baseline equation for teak was CATD = -0.05VPD+5.1which represents maximum values of CATD expected for zero transpiration in fully water stressed seedlings. For mahogany, lower baseline equation was CATD = -0.25VPD-2.9 and upper baseline equation was CATD = -0.01VPD+6.1. Jackson et al. (1981) showed that the limits, or baselines, are dependent on meteorological and plant factors. But it has to be noted that CATD of a crop is not rising above the non-water stressed baseline, indicating a mild water stress will not affect the productivity of plants. For both species the upper limit of CATD was found to be highly fluctuating. So the average values of CATD for the fully-stressed plants were used to develop upper baselines.

5.1.3. Crop Water Stress Index (CWSI)

CWSI exploit the relationship between canopy air temperature difference (CATD) and vapour pressure deficit (VPD) of the air. It gives a relative measure of water stress in plants. It was calculated separately for each treatment for both species. In theory, the CWSI (ldso et al., 1981) should progress from 0 for non-stressed plants transpiring at potential rates to 1 for severely stressed plants that are not transpiring. In the present study, it was found that the value of CWSI exceed the expected limits for both species. CWSI of well irrigated treatments of teak (IW/ET=1 and 0.6) ranged between -0.6 and 0.6. For mahogany, in treatment IW/ET=1 CWSI ranged from -1.9 to -0.4 and in IW/ET=0.6 the range was from -1.2 to 0.3. In treatments IW/ET=0 and IW/ET=0.3, CWSI remained positive throughout the experiment and sometimes exceeded the theoretical maximum limit of 'one' for both species. Occurrence of negative values and values greater than one have been reported in many other studies, such as those of Wanjura et al. (1984), Jalali-Farahani et al. (1994); Alderfasi and Nielsen (2001); Silva and Ramana (2005) etc. This results from the variability around the baselines. Other than VPD, environmental factors like net radiation and wind speed could influence the canopy temperature differences and it may reflect in CWSI also. Jones (1999; 2004) recommended that CWSI has not been used in all climates as it will not be accurate, especially under humid conditions. In order to check that a more detailed and accurate study is needed. The CWSI values in irrigated plots generally dropped following each irrigation application, and then increased steadily to a maximum value just prior to the next irrigation application as the soil water in the rhizosphere was depleted. But CWSI of IW/ET=0 remained without much fluctuation through the experiment.

5.1.4. Chlorophyll content

The observations revealed that significant reduction in chlorophyll content occurred during water stress in teak seedlings. Water stressed treatment IW/ET=0 showed minimum chlorophyll content compared to the other treatments. At the end of six months of treatment relative chlorophyll content was minimum in treatment IW/ET=0.3(0.37mg/g). Mahogany seedlings also exhibited the same pattern in chlorophyll content. Severe drought causes rupture of chloroplast and disintegration of chlorophyll molecules. Decreased or unchanged chlorophyll level during drought stress has been reported in many species, depending on the duration and severity of drought (Beltrano and Ronco, 2008; Nikolaeva et al., 2010). Many of the existing reports suggest that mild stress will not affect chlorophyll content (Manes et al., 2001, Duan et al., 2005, and Yanbao et al., 2006). So it can be assumed that irrigation at IW/ET=0.3 impose severe stress in seedlings of both species to impart chlorophyll content. Total chlorophyll content in seedlings of *Albizia lebbeck* and *Cassia siamea* was found to be less under water stress (Saraswathi, 2011).

5.1.5. Crude protein content

In teak seedlings no significant difference was observed in crude protein content under various levels of irrigation. In leaves of treatment IW/ET=1, crude protein content was 0.24 mg/g, in IW/ET=0.6, it was 0.21 mg/g and in IW/ET=0.3, crude protein content was measured as 0.22 mg/g. This might be because of high water use efficiency of teak seedlings to maintain normal photosynthetic rate even under mild water stress. The observation on treatment IW/ET=0 could not be done due to seedling mortality in prolonged water stress. Water stress usually reduce rate of leaf photosynthesis which may be because of damage of cellular structures (Tang et al., 2002) or due to a reduction in chlorophyll concentration (Mohsenzadeh et al., 2005). In mahogany treatment IW/ET=0.3 showed significant reduction in crude protein content (0.21 mg/g). In well watered treatments (IW/ET=1 and 0.6) the crude protein content recorded as 0.65 mg/g and 0.55 mg/g respectively. Further detailed studies are needed to correlate the photosynthetic rate and leaf crude protein content of plants under water stress.

5.1.6. Relative growth rate

As already mentioned, growth is known to be related to cell turgor. Reduced growth rate is one of the first responses of water stress in plants. Significant reduction in relative growth rate was observed among different levels of irrigation in teak as well as mahogany seedlings. Well irrigated seedlings of treatments (IW/ET=1 and 0.6) showed more relative growth rate. Non watered IW/ET=0 showed least increase in growth followed by IW/ET=0.3. Myers and Landsberg (1989) observed significant reduction in leaf area and relative growth rate of seedlings of *Eucalyptus maculata* (growing in mesic environment) and *E. brockwayi* (prefers arid environment). Seedlings of *Leucaena leucocephala* showed 50 per cent reduction in relative growth rate under severe stressed condition and 30 per cent reduction under moderately stressed condition (El-Juhany and Aref, 1999). Six month old seedlings of *Conocarpus erectus* and *Eucalyptus microtheca* also showed decrease in relative growth rate in response to water stress (Al-harbi, 2006). Decrease in average growth rate in response to water stress in seedlings of *Cinnamomum verum, Syzygium jambos, Memecylon eleagni* as 10–20 per cent (Schumacher et al., 2009). There are reports which correlate difference in relative growth rate to dry matter partitioning. They explain reduction in relative growth rate is attributed by reduced allocation of biomass to leaves, the site of photosynthesis (Poorter et al. 1990). But Norgren (1996) found no relationship between relative growth rates and dry matter partitioning between Scots pine and lodgepole pine seedlings. In leucaena, decreased relative growth rate in the water-stressed seedlings was found to be associated with the decrease in leaf dry weight and specific leaf area. From the current study, we can correlate reduction in relative growth rate to reduced number of leaves in teak seedlings under water stress. But in mahogany, even though no significant variation was observed in the number of leaves, the reduction in relative growth rate was prominent as a result of drought. Thus it appears that loss in turgor due to water stress, although not severe to cause reduction in leaves, could affect growth in mahogany.

5.2. Biometric parameters

5.2.1. Height

From the observations carried out on teak seedlings, it is apparent that irrigation influences height of seedlings. Treatment IW/ET=0 and IW/ET=0.3 showed a significant reduction in terms of height. The difference in height due to different levels of irrigation became prominent after 30 days of the treatment. Plants in treatment IW/ET=0 was rain fed during the first two months and still they started showing reduction in height which implicate that rainfall was not enough for the normal growth of seedlings. After two months the plants in treatment IW/ET=0 were transferred to rain out shelter and kept without irrigation. Seedlings in the treatment IW/ET=0 completely wilted after one month. No significant height difference was observed between seedlings of IW/ET=0 and IW/ET=0.3. This indicates irrigation at level IW/ET=0.3 was not enough to provide sufficient water supply for the growth of seedlings. When evaporation exceeds water supply, it creates drought stress which is characterized by the reduction of cell water content, diminished leaf water potential and turgor loss, closure of stomata and decrease in cell enlargement and growth. Many reports suggest the negative impact of water stress in plant growth (Anjum et al., 2003; Bhatt and Rao, 2005; Kusaka et al., 2005; Shao et al., 2008). Water stressed citrus seedlings showed 25 per cent reduction in plant height (Wu et al., 2008). Waring and Schlensinger (1985) suggested that decrease in predawn water potential is well correlated with a decreased tree height. Reduction in plant height up to 40 per cent of that of well irrigated seedlings as a result of 15 days exposure of water stress was observed in Eucalyptus and Casuarina seedlings (Nautiyal et al., 1994). Six month old seedlings of *Casuarina glauca*, under moderate and severe water stress, height lagged at 23 and 32 per cent behind that of well irrigated control plants

(Albouchi et al., 2003). Seedlings from treatment IW/ET=1 and IW/ET=0.6 showed more height. No significant difference was observed among seedlings of these two treatments which indicates, teak seedlings respond similarly under IW/ET=1 and IW/ET=0.6. This suggests irrigation at IW/ET=0.6 is enough for normal growth of teak seedlings.

The present study revealed that the given levels of irrigation did not affect the height growth of mahogany seedlings. This suggests increased drought tolerance of mahogany seedlings compared to teak seedlings. Even under non irrigated conditions seedlings were able to maintain normal height growth. Cordeiro et al. (2009) conducted a study to evaluate physiological and morphological responses of young mahogany plants to drought in the Amazon region under well-watered (pre-dawn leaf water potential, Ψ_{pd}, ca. -0.40 MPa) or drought (Ψ_{pd}, ca. -3.52 MPa). They reported normal height for seedlings under both treatments. Plant response, survival or susceptibility to various biotic and abiotic stresses varies with species, climate and silvicultural conditions. Al-harbi (2006) studied variation in height of six month old seedlings of two species *Conocarpus erectus* and *Eucalyptus microtheca* under sufficient irrigation, moderate water stress and severe water stress, and found that there is no significant variation in growth. Similar result was obtained in a study using two year old seedlings of *Quercus frainetto*, *Q. pubescens*, *Q. macrolepis* and *Q. ilex* also (Fotelli et al., 2000). Kallarackal and Somen (1995) reported that the water use characteristics of *Eucalyptus tereticornis* vary significantly when planted in two different sites.

5.2.2. Collar diameter

From the observations it is clear that water stress reduce collar diameter of teak seedlings. At the end of six months treatment, collar diameter varied from 8.5 mm in well watered IW/ET=1 to 6.6 mm in treatment IW/ET=0.3. IW/ET=0.6 showed mean collar diameter 7.7 mm and was on par with treatment IW/ET=1. Better performance in the seedlings of IW/ET=1 was observed among other treatments. This might be due to more availability of water in IW/ET=1 and IW/ET=0.6. In the other two treatments, water stress might influence the physiological processes and may result in poor performance of seedlings. It is known that high soil water availability facilitate nutrient accumulation, leaf growth, leaf area and number of leaves which converted more solar energy and fixed more CO_2 to produce more photosynthates, and thus greater growth and biomass production (Ceulemans et al., 1993). Sufficient soil water availability higher irrigation probably maintained cell turgidity and increased in leaf size and the overall biomass (Souch and Stephens, 1998). Result of this study found to be in agreement with Singh and Singh (2009). They reported collar diameter of two year old seedlings of *Dalbergia sissoo* was reduced by 38 per cent at low irrigation level. A 50 per cent reduction in collar diameter was observed in eucalyptus hybrid seedlings in response to moisture stress (Nautiyal et al, 1994). They observed similar pattern in Casuarina also. El-Juhany and Aref (1999) reported 23 and 35 per cent reduction in diameter in *Leucaena leucocephala* under moderate and severe water stress respectively. Moriana et al. (2003) mentioned trunk expansion as a sensitive indicator of water stress. In seedlings of *Persea americana* study done by Mngomba et al. (2010) indicated that o water application of 100 or 150 ml every two days interval increase growth and collar diameter significantly.

Water stress reduced collar diameter in mahogany seedlings also. At the end of six months IW/ET=1 had a mean collar diameter of 10.9 mm, Treatment IW/ET=0.6 showed 10.4 mm and IW/ET=0.3 had a mean collar diameter of 8.3 mm. This result was found to be in contrast with findings of Cordeiro et al. (2009). They did not observe any significant difference in collar diameter among well watered and non irrigated seedlings of mahogany which was explained as efficient use of remaining soil water, favoring cell turgor and expansion. In the present study, since the seedlings were raised in sufficiently long polythene bags which prevented the roots from going out in search of water. This might have lead to a condition that water was available only through irrigation. But in IW/ET=0, no irrigation was done and in IW/ET=0.3 the amount of water supplied may not be sufficient.

5.2.3. Number of leaves

Number of leaves was least in water stressed seedlings of teak. From the observations it is clear that treatment IW/ET=0.3 and IW/ET=0 showed significant reduction in number of leaves from the second fortnight of irrigation treatment. Shedding of leaves reveals the deciduous nature of the species. Total number of leaves in IW/ET=1, IW/ET=0.6 and IW/ET=0.3 were 12.6, 12.2 and 9.3 respectively at the end of six month period. Reduction in the number of leaves due to water stress is an efficient mechanism of plants to reduce loss of water through transpiration through reduction of leaf area. Drought tolerant species are characterized by more number of leaves with smaller size to keep rate of photosynthesis intact while reducing transpiration. Reduced number of leaves under water stress was observed in seedlings of Casuarina by Nautiyal et al. (1994). In *Leucaena leucocephala* reduction in number of leaves was estimated as 47 per cent and 65 per cent under moderate and severe water stress treatments respectively (El-Juhany and Aref, 1999). In one year old seedlings of four Mediterranean oak species, well irrigated seedlings showed more total leaf surface area and number of leaves compared to non irrigated ones (Fotelli et al., 2000).

It was noticed from the current study that different levels of irrigation was not enough to impart any significant change in total number of leaflets of mahogany. During the entire period under treatments, all the four treatments did not differ in the total number of leaflets. This result was in contrast with findings of Cordeiro et al. (2009). They observed 42 per cent decrease in leaflet numbers in drought stressed mahogany seedlings, which was due to leaf (leaflet) abscission. In the present study, both the species, teak and mahogany was raised under identical conditions and same levels of irrigation was applied, and was observed that mahogany retained some of the growth characters intact in all the four levels of treatment. But teak was found to be more sensitive to drought. This might be due to higher drought tolerance of mahogany when compared to teak seedlings of same age.

5.2.4. Shoot weight

Significant reduction in shoot weight was observed among teak seedlings provided with different irrigation regimes. At the end of six months of irrigation treatment, seedlings of IW/ET=1 showed maximum shoot weight of 8.7 g, followed by IW/ET=0.6 (7.9 g). Seedlings of IW/ET=0.3 showed least shoot weight (6.4 g). The reduction in shoot weight of least irrigated treatment IW/ET=0.3 was 26 per cent when compared to well irrigated IW/ET=1. This reveals that shoot growth is very sensitive to water stress in teak. Reduction in shoot weight in response to water stress might be due to a shift in dry matter allocation. Under water deficit the plant may tend to allocate more dry matter towards roots than the aboveground parts. Depletion of water reserves leads to reduced growth rates, which are, among others, attributed to the lower photosynthetic rates due to stomatal closure and also to the reduced functionality of the root system, which is unable to support the unhindered supply of the canopy with nutrients and water (Grattan et al., 2006; Bacelar et al., 2007). The rate of reduction in shoot weight in response to water stress is known to be a function of duration and intensity of stress and also the tolerance of the species. Under moderate and severe drought, reduction in stem weight of *Leucaena leucocephala* treatments was found to be 52 per cent and 65 per cent respectively (El-Juhany and Aref, 1999). Reduction in number of leaves in IW/ET=0.3 and IW/ET=0 also might affected the shoot growth negatively. This was found to be true for poplar also (Pregitzer and Friend, 1996; Snyder and Williams, 2007).

No significant variation was observed in shoot weight of mahogany seedlings of different treatments in the first two months. After two months of treatment, seedlings of IW/ET=0.3 and IW/ET=0 started showing a significant reduction. This trend continued upto the time of death of seedlings in IW/ET=0 which occurred after four months. After four month of treatment seedlings of IW/ET=0.3 was found to be increasing its shoot weight and remained as high as that of well watered treatments. Prolonged exposure to stress might be attributed acclimation to seedlings of treatment IW/ET=0.3. This observation also reveals that mahogany is more drought tolerant than teak.

5.2.5. Root length

In both species IW/ET=0.3 had the maximum root length at the end of six months. From six weeks, increase in root length became significant in teak seedlings of IW/ET=0. This pattern continued till the time of mortality of seedlings in that treatment. For mahogany seedlings in IW/ET=0 showed increased root length after ten weeks followed by seedlings of IW/ET=0.3. This might be due to seedling acclimation to drought stress on account of prolonged exposure. Well irrigated IW/ET=1 and 0.6 showed no significant variation, and showed lesser values than IW/ET=0.3. The increase in root length is considered as an adaptive response against water stress as it helps plants to absorb more water during stress period. In ten week old seedlings of *Acacia mangium* increased root growth capacity was observed due to water stress (Awang and Chavez, 1993). In *Leucaena leucocephala* seedlings also a slight increase in root length due to water stress was observed (El-Juhany and Aref, 1999). Pinheiro et al. (2005) observed well developed root system in drought tolerant clones of *Coffea canephora*. Increased root length can be considered as an efficient mechanism of plants to explore deeper layers of soil and hence to absorb more water to cope up with water stress.

5.2.6. Root weight

No significant variation in root weight was observed among seedlings of mahogany under different levels of irrigation. The same pattern was observed in drought affected seedlings of *Picea pubescens* by Robert and Cannon (1992). In teak seedlings, root weight was more in well irrigated treatments while root length was less. At the end of six months of irrigation treatment IW/ET=1 showed maximum root weight of 17.3 g followed by IW/ET= 0.6 having 16.6 g. Minimum root weight was shown by least irrigated treatment IW/ET=0.3 (13.2 g). El-Juhany and Aref (1999) estimated the reduction in root dry weight by 21 per cent under moderate and 29 per cent under severe water stress in Leucaena. As the seedlings show an increased root length in response to water stress, but no subsequent increase in root weight, we can assume that under drought affected teak seedlings produce thinner roots than in normal conditions. Under drought stress the plants may allocate more dry matter towards roots and roots keep on increasing its length in search of available water. Roots produced under drought stress may be thinner when compared to normal roots because the plant tends to increase root surface area to increase water absorption. According to Taiz and Zeiger (2006), a shoot will grow until it is so large that water uptake by the roots becomes limiting to further growth; conversely, roots will grow until their demand for photosynthate from the shoot equals the supply. This functional balance is shifted if the water supply decreases and results in an increased root growth.

5.2.7. Shoot-root length ratio

In the current study, increased shoot root length ratio was observed in less irrigated and non irrigated seedlings of teak. At the end of six months maximum shoot-root length ratio obtained is 1.9 from IW/ET=0.3. Treatment IW/ET=1 and 0.6 were on par with each other. The same pattern was observed in drought affected saplings of Eucalyptus (Rose et al., 1990 and Ngugi et al., 2004), sandal (Hiremath, 2004) etc. Bongarton and Teskey (1987) reported that, when juvenile plants are under water stress above-ground growth is affected more severely by water stress than below-ground growth. Shoot-root biomass ratio appears to be governed by a functional balance between water uptake by the root and photosynthesis by the shoot increased root growth. This functional balance is affected by water stress and more biomass is allocated towards roots to increase more water absorption.

In mahogany, there was no significant reduction in shoot-root ratio among different irrigation treatments upto 140 days. Later on IW/ET=0.3 showed reduced shoot root length ratio. Reduced shoot root ratio implies more growth of roots than shoot growth. Treatment IW/ET=1 and 0.6 were on par with each other and showed no reduction in shoot-root ratio.

5.2.8. Shoot-root biomass ratio

A significant reduction was observed in shoot-root biomass ratio of teak seedlings in IW/ET=0 after six weeks. This indicates that the rain was not sufficient to maintain the normal growth of seedlings. Later on IW/ET=0 was transferred to rain out shelter and maintained without any irrigation. But the shoot-root biomass ratio remained without any significant changes and continued to be inferior compared to other treatments. Reduction in shoot root biomass ratio is due to allocation of more biomass in the roots than the shoot in search of water under drought stress. This observation concurs with the result of McMillan and Wagner (1995); Ibrahim (1995); El-Juhany and Aref (1999). Rao et al. (2005) also reported reduced performance of teak seedlings under severe water stress in shoot-root biomass ratio. Same result was reported in *Hopea odorata* and *Mimusops elengi* seedlings (Zainudin et al., 2003); and in seedlings of *Dalbergia sissoo* (Singh and Singh, 2009).

In mahogany, no significant change in shoot-root biomass ratio was observed among different treatments. The levels of irrigation might not be sufficient to impart water stress in treatments IW/ET=1, 0.6 and 0.3. Mahogany seedlings maintained normal root weight and number of leaflets even under non irrigated condition even thought there was significant reduction in shoot weight. This might be a reason for normal shoot-root biomass ratio of IW/ET=0 when compared to other treatments.

The present series of investigations clearly indicate that water stress negatively affect growth and other physiological processes in teak and mahogany seedlings. But in teak, the stress symptoms appear to be more severe than in mahogany. Irrigation at IW/ET=0.3 is not sufficient for normal functioning in both species. It is interesting to note that seedlings of IW/ET=1 was not superior in any of the observed parameters over that of IW/ET=0.6 in both species. So it can be concluded that provision of more water will not give a corresponding increase in plant growth performance. Level of irrigation can be fixed to the lowest limit so that the plants will not suffer any water stress condition. CWSI has got immense potential for early detection of water stress in plants and this can be effectively utilized for calculating optimum irrigation requirement and for irrigation scheduling. Influence of other weather parameters like relative humidity, wind speed and soil physical properties on CWSI can also be investigated.

SUMMARY

SUMMARY

Studies to model crop water stress index (CWSI) in two important tree species was taken up in College of Forestry, Vellanikkara. The basic objective of the study was to detect water stress in seedlings of teak and mahogany with the help of infrared thermometry using CWSI. Seedlings were kept under a rain out shelter and irrigation was done at four different levels on weekly intervals calculated based on FAO Modified Penman's equation. Canopy temperature measurements were done each day using a hand held infrared thermometer in order to develop crop water stress index (CWSI) for both the species.

The salient findings of the study are given below.

Teak seedlings are more susceptible to water stress which died early than mahogany. Baseline equations for upper and lower boundary of canopy temperature were developed. For teak the lower baseline was determined as CATD = -1.01VPD+2.8 and the upper limit was CATD = -0.05VPD+5.1. For mahogany, lower baseline equation was CATD = -0.25VPD-2.9 and upper limit was CATD = -0.01VPD+6.1. Based on these baseline equations CWSI was computed for each treatment of both the species. For both species CWSI was found to be exceeding the theoretical limit of 0 to 1. But CWSI values in irrigated plots generally dropped following each irrigation application, and then increased steadily to a maximum value just prior to the next irrigation application. For well irrigated treatments of teak (IW/ET=1.0 and 0.6) CWSI was almost the same and showed a gradual increase from -0.2 to 0.2. For other two treatments of teak (IW/ET=0.3 and IW/ET=0) CWSI was high which indicates inadequate water supply. For mahogany CWSI ranges for different treatments were: - IW/ET=1.0 (-1.2 to -0.9), IW/ET= 0.6 (-0.4 to -0.2), IW/ET=0.3 (0.4 to 0.7). For IW/ET=0 it ranges from 0.8 to 0.9. Chlorophyll content was found to be less in non irrigated IW/ET=0 of both species followed by treatment IW/ET=0.3, while it was higher in well watered treatments. No significant reduction

in crude protein content was observed during the treatment period in case of teak seedlings. For mahogany in treatment with irrigation at IW/ET=0.3, there was a significant reduction in crude protein content. Well watered treatments showed higher crude protein content. This indicates a significant reduction in photosynthesis occurs during water stress in mahogany seedlings. For both the species relative growth rate (RGR) was more in well watered treatments (irrigation at IW/ET=1 and 0.6). Seedlings with irrigation at IW/ET=0.3 exhibited less RGR compared to well watered treatments. Control IW/ET=0 treatment showed minimum RGR. During the first two weeks of treatments teak seedlings showed uniform height growth. Later on IW/ET=0 and IW/ET=0.3 showed a significant reduction. Treatment with IW/ET=1 showed maximum height followed by treatment giving irrigation at IW/ET=0.6. In mahogany there was no much of height variation. Water stress in seedlings caused reduction in collar diameter in seedlings of teak and mahogany. Treatments provided with irrigation at IW/ET=0.3 showed a significant reduction where as other treatments (irrigation at IW/ET=1 and 0.6) showed equal performance. Water stress induced significant reduction in number of leaves in teak seedlings. In treatment with irrigation at IW/ET=0.3 it was minimum. Number of leaves in other two treatments (irrigation at IW/ET=1 and irrigation at IW/ET=0.6) showed no reduction in the number of leaves. No significant change in response to water stress was observed in total leaflet number of mahogany seedlings. Teak seedlings with irrigation at IW/ET=0.3 showed significant decline in shoot weight. No difference was observed between other two treatments (irrigation at IW/ET=1 and 0.6). No significant reduction was observed among various treatments of mahogany seedlings in shoot weight at the end of six months. Root length of teak seedlings with irrigation at IW/ET=0.3 was maximum, other two treatments showed a decrease in length, but not significantly different. Mahogany seedlings also showed similiar trend. Root weight was minimum in teak seedlings provided with minimum irrigation (IW/ET=0.3 and IW/ET=0). In mahogany, all treatments were alike in terms of root weight. Teak seedlings of treatment IW/ET=0 were superior throughout the experimental period in terms of shoot root length ratio. No significant difference was observed among the other treatments. In mahogany seedlings no significant difference was observed in shoot root length ratio between treatments except for seedlings with irrigation at IW/ET=0.3 which showed largest value. A significant reduction in root weight of teak seedlings were shown by seedlings provided with irrigation at IW/ET=0.3 and IW/ET=0. No significant difference was observed among well watered treatments (irrigation at IW/ET=1 and 0.6). For mahogany all treatments were alike in terms of root weight. In teak, shoot root length ratio of IW/ET=0 and IW/ET=0.3 was less compared to well watered treatments. For mahogany, up to the death of control seedlings, no significant difference was observed in shoot root length ratio. Later IW/ET=0.3 showed lesser performance compared to well watered treatments. No significant difference was observed in shoot root biomass ratio of seedlings of both species.

CONCLUSION

The present study on "Modeling crop water stress (CWSI) in tree seedlings" was successful in developing equations for upper and lower stress baselines for teak and mahogany to find out CWSI. For teak the lower baseline was determined as CATD = -1.01VPD+2.8 (R^2=0.86) and the upper baseline equation was CATD = -0.05VPD+5.1 (R^2=0.61). For mahogany, lower baseline equation was CATD = -0.25VPD-2.9 (R^2=0.79) and upper baseline equation was CATD = -0.01VPD+6.1 (R^2=0.58). Canopy temperature is a promising tool for detection of crop water stress prior to its adverse effect on growth and other physiological processes of plants. Canopy air temperature difference was found to be low in water stressed plants when compared to well irrigated plants. It has been found that leaf temperature of mahogany is always lower than that of teak. Effect of different levels of stress in physiological and biometric characteristics of teak and mahogany seedlings was identified. Mahogany seedlings showed more stress tolerance when compared to teak seedlings.

REFERENCES

REFERENCES

Abebe, T. 1994. Growth performance of some multipurpose trees and shrubs in the semi-arid areas of Southern Ethiopia. Agroforest. Sys., 26: 237-248.

Aber, J.D. and Melillo, J.M. 1991. *Terrestrial Ecology*. Saunders College Publishing, A division of Holt, Rinehart and Winston, Inc. New York, 430p.

Ajayi, A.E. and Olufayo, A.A. 2004. Evaluation of two temperature stress indices to estimate grain sorghum yield and evapotranspiration. Agron. J., 96: 1282-1287.

Albouchi, A., Bejaoui, Z., and Aouni, M.H.E. 2003. Influence of moderate or severe water stress on the growth of *Casuarina glauca* Sieb. seedlings. Sci. et changements plaetaires, 14 (3): 137-142.

Alderfasi, A.A. and Nielsen, D.C. 2001. Use of crop water stress index for monitoring water status and scheduling irrigations in wheat. Agric. Water Manage., 47; 69-75.

Al-harbi, A.A.A. 2006. Effects of water deficit on the growth and physiological performance of *Conocarpus erectus* and *Eucalyptus microtheca* under field conditions. MSc. Thesis. College of Food Sciences and Agriculture, King Saud University, Saudi Arabia.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration. FAO Irrigation and Drainage Paper 56. FAO, Rome, 299p.

Angelopoulos, K., Dichio, B., and Xiloyannis, C. 1996. Inhibition of photosynthesis in olive trees (*Olea europaea* L.) during water stress and rewatering. J. Exp. Bot., 301 (47): 1093-1100.

Anjum, F., Yaseen, M., Rasul, E., Wahid, A., and Anjum, S. 2003. Water stress in barley (*Hordeum vulgare* L.). I. Effect on morphological characters. Pakistan J. Agric. Sci., 40: 43-44.

Ashraf, M.Y., Azmi, R.A., Khan, H.A., and Ala, A.S. 1994. Effect of water tress on total phenols, peroxides activity and chlorophyll content in wheat. Acta Physiol. Plant., 16 (3): 185-191.

Awang, K. and Chavez, C.G. 1993. Effect of root-wrenching and controlled watering on growth, drought resistance and quality of bare-rooted seedlings of *Acacia mangium*. J. Trop. For. Sci., 5: 309-321.

Bacelar, E.A., Pereira, J.M.M., Goncalves, B.C., Ferreira, T.C., and Correia, C.M. 2007. Changes in growth, gas exchange xylem hydraulic properties and water use efficiency of three olive cultivars under contrasting water availability regimes. Environ. Exp. Bot., 60: 183-192.

Bahuguna, V.K. and Lal, P. 1992. Standardization of nursery techniques of *Acacia auriculiformis* A. Cum Ex Benth under North Indian mist climatic conditions. Part-1. Method of seed sowing and irrigation schedule. Indian For., 118 (9): 616-622.

Bala, N., Singh, G., and Bohra, N.K. 2003. Effect of irrigation on growth and performance of three different tree species in Indian arid zone. Ann. Arid Zone, 42: 61-67.

Bates, L.M. and Hall, A.E., 1981. Stomatal closure with soil moisture depletion not associated with changes in bulk water status. Oecologia, 50: 62-65.

Beltrano, J. and Ronco, M.G. 2008. Improved tolerance of wheat plants (*Triticum aestivum* L.) to drought stress and rewatering by the arbuscular mycorrhizal fungus *Glomus claroideum*: Effect on growth and cell membrane stability. Brazilian J. Plant Physiol., 20: 29-37.

Bhatt, R.M. and Rao, N.K.S. 2005. Influence of pod load response of okra to water stress. Indian J. Plant Physiol., 10: 54-59.

Bongarten, B. C. and Teskey, R. O. 1987. Dry weight partitioning and its relationship to productivity in loblolly pine seedlings from seven sources. For. Sci., 33: 255-267.

Boughalleb, F. and Hajlaoui, H. 2011. Physiological and anatomical changes induced by drought in two olive cultivars (cv. Zalmati and Chemlali). Acta Physiol. Plant., 33: 53-65.

Brar, G.S., Kar, S., and Singh, N.T. 1990. Photosynthetic response of wheat to soil water deficits in the tropics. J. Agron. Crop Sci., 164: 343-348.

Broncano, M.J., Riba, M., and Retana, J. 1998. Seed germination and seedling performance of two Mediterranean tree species, Holm oak (*Quercus ilex* L.) and Aleppo pine (*Pinus halepensis* Mill.): a multifactor experimental approach. Plant Ecol., 138: 17-26.

Burgess, S.S.O., Adams, M.A., Turner, N.C., White, D.A., and Ong, C.K., 2001. Tree roots: conduits for deep recharge of soil water. Oecologia, 126: 158-165.

CAB, 2000. Forestry Compendium, Global Module, CD ROM. Centre for Agricultural Bioscience International, UK.

Cannell, M.G.R., Bridgewater, F.E., and Greenwood, M.S. 1978. Seedling growth rates, water stress responses and root-shoot relationships related to eight-year volumes among families of *Pinus taeda* L. Silvae Genet., 27: 237-248.

Canto, S.G., Tejada, Z.P., Munoz, J.J., Sobrino, J., de Miguel, E., and Villalobos, F.J. 2006. Detection of water stress in an olive orchard with thermal remote sensing imagery. Agric. For. Met., 136: 44.

Castrilo, M. and Calcagno, M.A. 1984. Effects of water stress and rewatering on ribulose 1,5 biphosphate carboxylase activity, chlorophyll and protein contents in two cultivars of tomato. J. Hort. Sci., 64 (6): 717-724.

Cermak, J., Matyssek, R., and Kucera, J. 1993. Rapid response of large, drought-stressed beech trees to irrigation. Tree Physiol., 12: 281-290.

Ceulemans, R.J., Pontailler, F.M., and Guittet, J. 1993. Leaf allometry in young poplar stands: reliability of leaf area index estimation, site and clone effects. Biomass Bioenerg., 4: 769-776.

Clawson, K.L. and Blad, B.L. 1982. Infrared thermometry for scheduling irrigation of corn. Agron. J., 74: 311-316.

Cohen, Y., Alchanatis, V., Meron, M., Saranga, Y., and Tsipris, J. 2005. Estimation of leafwater potential by thermal imagery and spatial analysis. J. Exp. Bot., 56: 1843-1852.

Cordeiro, Y.E.M., Pinheiro, H.A., Filho, B.G.S., Correa, S.S., Silva, J.R.R., and Dias- Filho, M.B. 2009. Physiological and morphological responses of young mahogany (*Swietenia macrophylla* King) plants to drought. For. Ecol. Manage., 258: 1449-1455.

Cornic, G. 2000. Drought stress inhibits photosynthesis by decreasing stomatal aperture- Not by affecting ATP synthesis. Trends Plant Sci., 5: 187-198.

Cremona, M.V., Stutzel, H., and Kage, H. 2004. Irrigation scheduling of kholrabi (*Brassica oleracea* var. Gongylodes) using crop water stress index. Hort. Sci., 39 (2): 276-279.

Curtis, O.F. 1936. Leaf temperatures and the cooling of leaves by radiation. Plant Physiol., 11: 343-364.

Curtis, O.F., Wallace, R.H., and Clum, H.H. 1938. "Leaf temperatures": a critical analysis with additional data. Am. J. Bot., 25: 761-771.

Deborah, L.B. and Bruce, B.G. 1998. Photosynthetic capacity and dry mass partitioning in dwarf and semi-dwarf wheat (*Triticum aestivum*). J. Plant Physiol., 153: 558-568.

Driessche, R. 1991. Influence of container nursery regimes on drought resistance of seedlings following planting. II. Stomatal conductance,specific leaf area, and root growth capacity. Can. J. For. Res., 21: 566-572.

Duan, B., Lu, Y., Yin, C., Junttila, O., and Li, C. 2005. Physiological responses to drought and shade in two contrasting *Picea asperata* populations. Physiol. Plant., 124: 476-484.

Eaton, F.M. and Belden, G.O. 1929. Leaf temperatures of cotton and their relation to transpiration, varietal differences, and yields. USDA Tech. Bull. 91: 1-39.

Edalat, M., Ghadiri, H., and Parsa, Z. 2010. Corn crop water stress index under different redroot pigweed (*Amaranthus retroflexus* L.) densities and irrigation regimes. Arch. Agron. Soil Sci., 56: 285-293.

Ehrler, W.L. 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors. Agron. J., 65 (3): 404-409.

Ehrler, W.L., Idso, S.B., Jackson, R.D., and Reginato, R.J., 1978. Wheat canopy temperature: relation to plant water potential. Agron. J., 70: 251-256.

El-Juhany, L.I. and Aref, I.M. 1999. Growth and dry matter partitioning of *Leucaena leucocephala* (Lam.) de Wit. trees as affected by water stress. Alexandria, J. Agric. Res., Egypt, 44 (2): 237-259.

Emekli, Y., Bastug, R., Buyuktas, D., and Emekli, N.Y. 2007. Evaluation of a crop water stress index for irrigation scheduling of bermudagrass. Agric. Water Manage., 90: 205-212.

Erdem, Y., Erdem, T., Orta, A.H., and Okursoy, H. 2005. Irrigation scheduling for watermelon with crop water stress index (CWSI). J. Cent. Eur. Agric., 6 (4): 449-459.

Erdem, T., Erdem, Y., Orta, A.H. and Okursoy, H. 2006. Water yield relationships of potato under different irrigation methods and regimes. Sci. Agric., 63: 226- 231.

Erdem, Y., Arin, L., Erdem, T., Polat, S., Deveci, M., Okursoy, M., Huseyin, T., and Gultas, H.T. 2010. Crop water stress index for assessing irrigation scheduling of drip irrigated broccoli (*Brassica oleracea* L. var. italica) Agric. Water Manage., 98: 148-156.

Fangmeier, D.D., Garrot, D.J., Husman, S.H., and Perez, J., 1989. Cotton water stress under trickle irrigation. Trans. ASAE., 32: 1955-1959.

Fernandes, E.J. and Turco, J.E.P. 2003. Reference evapotranspiration for irrigation management in soybean crop. Irrig., 8 (2): 132-141.

Fischer, G., Shah, M., Velthuizen, H., and Nachtergaele, F.O. 2001. Global agro-ecological assessment for agriculture in the 21st century. IIASA and FAO, Laxenburg, Austria.

Fotelli, M.N., Radoglou, K.M., and Constantinidou, H.I.A. 2000. Water stress responses of seedlings of four Mediterranean oak species. Tree Physiol., 20: 1065-1075.

Fuchs, M. and Tanner, C.B., 1966. Infrared thermometry of vegetation. Agron. J., 58: 597-601.

Garau, A.M., Lemcoff, J.H., Ghersa, C.M., and Beadle, C.L. 2008. Water stress tolerance in *Eucalyptus globulus* Labill. subsp. Maidenii (F. Muell.) saplings induced by water restrictions imposed by weeds. For. Ecol. Manage., 255: 2811-2819.

Gardner, B.R., 1979. Plant and canopy temperatures in corn as influenced by differential moisture stress. M.Sc. Thesis, University of Nebraska, 119p.

Gardner, B.R., Blad, B.L., and Watts, D.G. 1981. Plant and air temperature in differentially-irrigated corn. Agric. Met., 25: 207-217.

Gardner, B.R., Nielsen, D.C., and Shock, C.C. 1992. Infrared thermometry and the crop water-stress index. 2. Sampling procedures and interpretation. J. Prod. Agric., 5: 466-475.

Gencoglan, C. and Yazar, A. 1999. Determination of crop water stress index (CWSI) and irrigation timing by utilizing infrared thermometer values on the first corn grown under Cukurova conditions. Turkish J. Agric. For., 23: 87-95.

Gindaba, J. 2004. Water and nutrient relations of selected indigenous and exotic tree species of Ethiopia and the implications for their use in land rehabilitation. In: *Symp. Rehabilitation of Dryland Forests in Ethiopia: Ecol. Manage*. Muys, B., Gebrehiwot, K. and Bruneel, S. (eds.). 21-24 Sept., 2004. Mekelle, Ethiopia, pp 62.

Gindaba, J., Rozanov, A., and Negash, L. 2004. Response of seedlings of two Eucalyptus and three deciduous tree species from Ethiopia to severe water stress. For. Ecol. Manage., 201: 119-129.

Giuliani, R., Magnanini, E., and Flore, J.A. 2001. Potential use of infrared thermometry for the detection of water deficit in apple and peach orchards. In: *Proc. 7th Int. Symp. Orchard Planting Syst.*, ISHS. Palmer, J.W. and Wunsche, J.N. (eds.). Acta Hort., 557: 399-405.

Gontia, N.K. and Tiwari, K.N. 2008. Development of crop water stress index of wheat crop for scheduling irrigation using infrared thermometry. Agric. Water Manage., 95 (10): 1144-1152.

Gonzalez-Dugo, M.P., Moran, M.S., Mateos, L., and Bryant, R. 2006. Canopy temperature variability as an indicator of crop water stress severity. Irrig. Sci., 24; 233-240.

Grace, J. 1999. Environmental controls of gas exchange in tropical rain forests. In: *Physiological plant ecology*. Press, M.C., Scholes, J.D., and Barker, M.G. (eds.). British Ecological Society. London, UK. 367-390p.

Grattan, S.R., Berenguer, M.J., Connell, J.H., Polito, V.S., and Vossen, P.M. 2006. Olive oil production as influenced by different quantities of applied water. Agric. Water Manage., 85: 133-140.

Gross, K.L. 1984. Effects of seed size and growth from on seedling establishment of six monocarpic perennial plants. J. Ecol., 72: 369-378.

Guerfel, M., Baccuri, O., Boujnah, D., Chibi, W. and Zarrouk, M. 2008. Impacts of water stress on gas exchange, water relations, chlorophyll content and leaf structure in the two main Tunisian olive (*Olea europaea* L.) cultivars. Sci. Hort., 119 (3): 257-263.

Hiremath, A.J. (ed.). 2004. Special Section on 'Non-timber forest products'. Conservation and Society. Available at http://www.conservationandsociety.org/vol-2-2-04.html. Accessed on 12 Jan. 2011.

Hoffman, G.F., Howell, T.A., and Solomon, K.H. 1990. Management of Farm Irrigation Systems. ASAE Monograph. New York, 155-203.

Ibrahim, L. 1995. Effects of nitrogen supply, water stress, and interaction between water and nitrogen on assimilate partitioning in poplar. Ph. D. thesis. University of Aberdeen, UK.

Ibrahim, L., Proe, M.F., and Cameron, A.D. 1997. Main effects of nitrogen supply and drought stress upon whole plant carbon allocation in poplar. Can. J. For. Res., 27: 1412-1419.

Idso, S.B. 1982. Non-water-stressed baselines: a key to measuring and interpreting plant water stress. Agric. Met. 27: 59-70.

Idso, S.B., Baker, D.G., and Gates, D.M. 1966. The energy environment of plants. In: Advances in Agronomy. Vol.18. Norman, A.G. (ed.). Academic press, New York, pp 171-218.

Idso, S.B., Hatfield, J.L., Jackson, R.D., and Reginato, R.J. 1979. Grain yield prediction: Extending the stress-degree-day approach to accommodate climatic variability. Remote sensing Environ., 8: 267-272.

Idso, S.B., Jackson, R.D., and Reginato, R.J. 1977. Remote sensing of crop yields. Sci., 196: 19-25.

Idso, S.B., Jackson, R.D., and Reginato, R.J. 1978. Extending the "degree day" concept of phenological development to include water stress effects. Ecol., 59: 431-433.

Idso, S.B., Jackson, R.D., Pinter Jr.P.J., Reginato, R.J., and Hatfield, J.L. 1981. Normalizing the stress degree- day for environmental variability. Agric. Met., 24: 45-55.

Idso, S.B., Reginato, R.J., Hatfield, J.L., Walker, G.K., Jackson, R.D., and Pinter, Jr.P.J. 1980. A generalization of the stress-degree-day concept of yield prediction to accommodate a diversity of crops. Agric. Met., 21: 205-211.

Irmak, S., Haman, D.Z., and Bastug, R. 2000. Determination of crop water stress index for irrigation timing and yield estimation of corn. Agron. J., 92 (6): 1221-1227.

Jackson, R.D., Idso, S.B., Reginato, R.J., and Pinter, Jr.P.J. 1981. Canopy temperature as a drought stress indicator. Water Resour. Res., 17: 1133-1138.

Jalali-Farahani, H.R., Slack, D.C., Kopec, D.M., and Mathias, A.D., 1993. Crop water stress index for bermudagrass turf: a comparison. Agron. J., 85: 1210- 1217.

James, S.A. and Bell, D.T. 2000. Leaf orientation, light interception and stomatal conductance of *Eucalyptus globulus* ssp. Globulus leaves. Tree Physiol., 20: 815-823.

Jones, H.G. 1990. Physiological aspects of the control of water status in horticultural crops. Hort. Sci., 25: 19-25.

Jones, H.G. 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. Agric. For. Met., 95: 139-149.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. J. Exp. Bot., 55 (407): 2427-2436.

Kadambi, K. 1972. "Silviculture and management of Teak" Bull., School of Forestry, Austin State University, USA. 137p.

Kallarackal, J. and Somen, C.K. 1992. "Water use of selected indigenous and exotic trees", KFRI Research Report 86, Peechi, Kerala, India.

Kallarackal, J. and Somen, C.K. 1995. Water use by *Eucalyptus tereticornis* stands of differing density in Southern India. Tree Physiol., 17: 195-203.

Kaosaard, A. 1981. Teak: Its natural distribution and related factors. Nat. Hist. Bull. Siam. Soc., 29: 55-74.

Keener, M.E. and Kircher, P.L. 1983. The use of the canopy temperature as an indicator of drought stress in humid regions. Agric. Met., 28: 339-349.

Kireger, E.K. and Blake, T.J. 1994. Genetic variation in dry matter production, water use efficiency and survival under drought in four acacia species. Adv. Geoecol., 27: 195-204.

Kirnak, H. and Dogan, E. 2009. Effect of seasonal water stress imposed on drip irrigated second crop watermelon grown in semi-arid climatic conditions. Irrig. Sci., 27 (2): 155-164.

Kirnak, H., Copur, O., Doan, E., Bahceci, I., Demir, S., and Tonkaz, T. 2005. Evaluation of relationship between crop water stress index and generative-fiber characteristics of cotton. GAP IV. Tarim Kong, Anliurfa, pp 1164-1171.

Kozlowski, T.T. (ed.). 1968. *Water Deficits and Plant Growth,* Vol. I. Academic Press, New York, 336p.

Kozlowski, T.T. 1982. Water supply and tree growth (II). Flooding. For. Abstr., 43: 145-161.

Kozlowski, T.T. and Davies, W.J. 1975. Control of water balance in transplanted trees. J. Arboric., 1: 1-10.

Kozlowski, T.T., Kramer, P.J., and Pallardy, S.G. 1991. *The Physiological Ecology of Woody Plants*. Academic Press, USA, 657p.

Kramer, P.J. 1969. *Plant and Soil Water Relationships: A Modern Synthesis*. McGraw-Hill Book Company, New York, 482p.

Kramer, P.J. and Boyer, J.S. 1995. *Water Relations of Plants and Soils,* Academic Press, USA, 496.

Kulshreshtha, S., Mishra, D.P., and Gupta, R.K. 1987. Changes in content of chlorophyll, proteins and lipids in whole chloroplast and chloroplast membrane fractions at different leaf water potentials in drought resistant and sensitive genotypes of wheat. Photosynthetica, 21 (1): 65-70.

Kusaka, M., Ohta, M. and Fujimura, T. 2005. Contribution of inorganic components to osmotic adjustment and leaf folding for drought tolerance in pearl millet. Physiol. Plant., 125: 474-489.

Lambers, H., Chapin, F.S., and Pons, T.L. 1998. *Plant Physiological Ecology*, Springer-Verlag, New York Inc. 540p.

Law, B.E., Williams, M., Anthoni, P.M., Baldochi, D.D., and Unsworth, M.H. 2000. Measuring and modelling seasonal variation of carbon dioxide and water vapour exchange of a *Pinus ponderosa* forest subject to soil water deficit. Global Change Biol., 6: 613-630.

Li, C. and Wang, K. 2003. Differences in drought responses of three contrasting *Eucalyptus microtheca* F.Muell. populations. For. Ecol. Manage., 179: 377- 385.

Li, C., Berninger, F., Koskela, J., and Sonninen, E. 2000. Drought responses of *E. microtheca* provenances depend on seasonality of rainfall in their place of origin. Aust. J. Plant Physiol., 27: 231-238.

Lowry, O.H., Rosebrough, N.J., Farr, A.L., and Randall, R.J. 1951. Protein measurement with the Folin-Phenol reagents. J. Biol. Chem., 193: 265-275.

Majken, P., Claudia, B., and Hans, B. 2005. Tolerance and physiological responses of *Phragmites australis* to water deficit. Aqua. Bot., 81: 285-299.

Manes, F., Donato, E., and Vitale, M. 2001. Physiological response of *Pinus halepensis* needles under ozone and water stress conditions. Physiol. Plant., 113: 249-257.

McDonald, S.E. 1984. Irrigation in forest-tree nurseries: Monitoring and effects on seedling growth. In. *Forest Nursery Manual*. Duryea, M.L. and Landis, T.D. (eds.). Nijhoff Junk Publishers. pp 107-121.

McKersie, B.D. and Leshem, Y.Y. 1994. *Stress and Stress Coping in Cultivated Plants*, Kluwer Academic Publishers, Netherlands, 256p.

McMillan, J.D. and Wagner, M.R. 1995. Effects of water stress on biomass partitioning of ponderosa pine seedlings during primary root growth and shoot periods. For. Sci., 41 (3): 594-610.

Meron, M., Tsipris, J., Orlov, V., Alchanatis, V., and Cohen, Y. 2010. Crop water stress mapping for site specific irrigation by thermal imagery and artificial reference surfaces. Precision Agric., 11: 148-162.

Metcalfe, J.C., Davies, W.J., and Pereira, J.S. 1990. Leaf growth of *Eucalyptus globulus* seedlings under water deficit. Tree Physiol., 6: 221-227.

Miller, E.C. and Saunders, A.R. 1923. Some observations on the temperature of the leaves of crop plants. J. Agric. Res., 26: 15.

Mngomba, S.A., Akinnifesi, F.K., Sileshi, G., Mhango, J., Ajayi, O.C., Chilanga, T.G., and Jamnadass, R. 2010. Early soil and water management effects on *Uapaca kirkiana* and *Vangueria infausta* fruit productivity. Discussion paper, 2nd World Agroforestry congress. Aug. 2009. Nairobi, Kenya.

Mohsenzadeh, S., Malboobi, M.A., Razavi, K., and Farrahi-Aschtiani, S. 2005. Physiological and molecular responses of *Aeluropus lagopoides* (Poaceae) to water deficit. Environ. Exp. Bot. 56: 314-322.

Mokotedi, M.E.O., Watt, M.P., and Pammenter, N.W. 2000. Invitro rooting and subsequent survival of two clones of a cold-tolerant *Eucalyptus grandis* x *E. nitens* hybrid. Hort. Sci., 35: 1163-1165.

Moller, M., Alchanatis, V., Cohen, Y., Meron, M., Tsipris, J., Naor, A., Ostrovsky, V., Sprintsin, M., and Cohen, S. 2007. Use of thermal and visible imagery for estimating crop water status of irrigated grapevine., J. Exp. Bot., 58: 827-838.

Monteith, J., and Szeicz, G. 1962. Radiative temperature in the heat balance of natural surfaces. Q. J. R. Met. Soc., 88: 496-507.

Moriana, A., Orgaz, F., Pastor, M., and Fereres, E. 2003. Yield responses of a mature olive orchard to water deficits. J. Am. Soc. Hort. Sci., 128: 425-431.

Muthuchelian, K., Murugan, C., Nedunchezhian, N., and Kukandaivelu, G. 1997. Photosynthesis and growth of *Erythrina variegata* as affected by water stress and triacontanol. Photosynthetica 33: 241-248.

Myers, B.J. and Landsberg, J.J. 1989. Water stress and seedling growth of two eucalyptus species from contrasting habitats. Tree Physiol., 5: 207-218.

Nakayama, F.S. and Bucks, D.A. 1983. Application of a foliage temperature based crop water-stress index to Guayule. J. Arid Environ. 6: 269-276.

Nautiyal, S., Pokhriyal, T.C. and Emmanuel, C.J.S.K. 1994. Natural regeneration of *Eucalyptus camaldulensis*: a new report. Indian For., 120: 174-175.

Nevo, E., Bolshakova, M.A., Martyn, G.I., Musatenko, L.I., Sytnik, K.M., Pavlieek, T., and Baharav, A. 2000. Drought and light anatomical adaptive leaf strategies in three woody species by microclimatic selection at ‘‘Evolution Canyon’’. Israel J. Plant Sci., 48: 33-46.

Ngugi, M.R., Hunt, M.A., Doley, D., Ryan, P., and Dart, P. 2004. Selection of species and provenances for low-rainfall areas: physiological responses of *Eucalyptus cloeziana* and *Eucalyptus argophloia* to seasonal conditions in subtropical Queensland. For. Ecol. Manage., 193: 141-156.

Nielsen, D.C. 1990. Scheduling irrigations for soybeans with crop water stress index (CWSI). Field Crops Res., 23: 103-116.

Nielsen, D.C. and Anderson, R.L. 1989. Infrared thermometry to measure single leaf temperatures for quantification on water stress in sunflower. Agron. J., 81: 840-842.

Nielsen, D.C. and Gardner , B.R. 1987. Scheduling irrigations for corn with crop water stress index (CWSI). Appl. Agric. Res., 2: 295- 300.

Nikolaeva, M.K., Maevskaya, S.N., Shugaev, A.G., and Bukhov, N.G. 2010. Effect of drought on chlorophyll content and antioxidant enzyme activities in leaves of three wheat cultivars varying in productivity. Russian J. Plant Physiol., 57: 87-95.

Nilsen, E.T. and Orcutt, D.M. 1996. *The Physiology of Plants Under Stress. Abiotic Factors*, John Willey and Sons, USA. 683p.

Norgren, O. 1996. Growth analysis of Pinus sylvestris and lodgepole pine seedlings. For. Ecol. Manage., 86: 15-26.

Odemis, B. and Bastug, R. 1999. Assessing crop water stress and irrigation scheduling in cotton through use of infrared thermometry technique. Trend. J. Agric. For. 23: 31-37.

Orta, A.H., Erdem, T., and Erdem , Y. 2002. Determination of water stress index in sunflower. Helia, 37: 27-38.

Orta, A.H., Erdem, Y., and Erdem, T. 2003. Crop water stress index for watermelon. Sci. Hort., 98: 121-130.

Ovcharova, A. and Nedkov, N. 2005. Relationship between canopy air temperature differences of peppermint (*Menta piperita* L.), irrigation requirement and crop yield. Bulgarian J. Agric. Sci., 11: 415-422.

Parsons, L.R. 1982. Plant responses to water stress. In: *Breeding Plants for Less Favorable Environments*. Christiansen, M. N. and Lewis, C. F. (eds.). Wiley, New York, pp 175-192.

Payero, J.O. and Irmak, S. 2006. Variable upper and lower crop water stress index baselines for corn and soybean. Irrig. Sci., 25: 21-32.

Payero, J.O., Neale, C.M.U., and Wright, J.L. 2005. Non-water-stressed baselines for calculating crop water stress index (CWSI) for alfalfa and tall fescue grass. Trans. ASAE, 48 (2): 653-661.

Pereira, A.A. and Riekerk, H., 1990. Water balance of *Eucalyptus globulus* and *Quercus suber* forest stands in Southern Portugal. For. Ecol. Manage., 38: 55-64.

Pereira, J.S., Tenhunen, J.D., Lange, O.L., Beyschlag, W., Meyer, A. and David, M.M. 1986. Seasonal and diurnal patterns in leaf gas exchange of *Euculyptus globulus* trees growing in Portugal. Can. J. For. Res., 16:177-184.

Pereira, L.S., Oweis, T., and Zairi, A. 2002. Irrigation management under water scarcity. Agric. Water Manage., 57: 175-206.

Pessin, L.J. 1939. Density of stoching and character of ground cover a factor in longleaf pine reproduction. J. For., 37: 255-258.

Phillips, J.G. and Riha, S.J. 1993. Canopy development and solar conversion efficiency in *Acacia auriculiformis* under drought stress. Tree Physiol., 12 (2): 137-149.

Pinheiro, H.A., DaMatta, F.M., Chaves, A.R.M., Loureiro, M.E., and Ducatti, C. 2005. Drought tolerance is associated with rooting depth and stomatal control of water use in clones of *Coffea canephora*. Ann. Bot., 96: 101-108.

Pinter, Jr.P.J. and Reginato, R.J. 1982. A thermal infrared technique for monitoring cotton water stress and scheduling irrigation. Trans. ASAE, 25: 1651-1655.

Pohjonen, V. 1989. Establishment of fuel wood plantations in Ethiopia. Silva Cerelica, 14: 1-388.

Poorter, H., Remkes, C., and Lambers, H. 1990. Carbon and nitrogen economy of 24 wild species differing in relative growth rate. Plant Physiol., 94: 621-627.

Pregitzer, K.S. and Friend, A.L. 1996. The structure and function of Populus root systems. In: *Biology of Populus and its Implication for Management and Conservation*. Stettler, R.F., Bradshaw, H.D., Heilman, P.E., and Hinckley, T.M. (eds.). NRC Research Press, National Research Council of Canada, Ottawa, pp 331-354.

Rajendrudu, G. and Naidu, C.V. 1998. Effect of water stress on leaf growth and photosynthetic and transpiration rates of *Tectona grandis*. Biol. Plant., 40: 229-234.

Rameaux, 1843. Des temperaturs vegetales. Ann. Sci. Nat. Bot. Biol. Veg., 19 (2): 10.

Randall, S.A., Thornber, P., and Fiscus, E. 1977. Water stress effects on the content and organization of chlorophyll in mesophyll and Bundle sheath chloroplasts of maize. Plant Physiol., 59: 351-353.

Rao, P.B. 1988. Effect of environmental factors on germination and seedling growth in *Quercus floribunda* and *Cupressus torulosa* tree species of Central Himalaya. Ann. Bot. 61: 531-540.

Rao, P.B. 2005. Effect of shade on seedling growth of five important tree species in Tarai region of Uttaranchal. Bull. Natl. Inst. Ecol., 15: 161-170.

Rao, P.B. and Singh, S.P. 1984. Response breadths on environmental gradients on germination and seedling growth in two dominant tree species of Central Himalaya. Ann. Bot. 56: 783-794.

Rao, P.B., Kaur, A., and Tewari, A. 2008. Drought resistance in seedlings of five important tree species in Tarai region of Uttarakhand. Tropical Ecol., 49 (1): 43-52.

Raven, P.H., Evert, R.F., and Eichhorn, S.E. 1986. *Biology of Plants*. Worth Publishers, New York, 775p.

Rawat, P.S., Gupta, B.B., and Rawat, J.S. 1985. Transpiration, stomatal behaviour and growth of Eucalyptus hybrid seedlings under different soil moisture levels. Indian For., 111: 1095-1110.

Ray, J.P. and Alcantara, J.M. 2004. Seedling establishment in *Olea europaea*: Seed size and micro habitant affect growth and survival. Ecoscience, 11 (1): 310-318.

Reginato, R.J. and Howe, J. 1985. Irrigation scheduling using crop indicators. J. Irrig. Drain. Engng., 3: 125-133.

Reginato, R.J., Idso, S.B., and Jackson, R.D. 1978. Estimating forage crop production: a technique adaptable to remote sensing. Remote Sens. Environ., 7: 77-80.

Rincon, H.P., and Chapin, F.S.E.1998. Effect of changing light availability on nutrient foraging in tropical deciduous tree-seedlings. Oikos, 82: 449- 458.

Roberts, B.R. and Cannon, W.N. 1992. Growth and water relationships of red spruce seedlings exposed to atmospheric deposition and drought. Can. J. For. Res., 22: 193-197.

Rolando, C.A. and Little, K.M. 2008. Measuring water stress in *Eucalyptus grandis* Hill ex Maiden seedlings planted in pots. South Afr. J. Bot., 74: 133-138.

Rose, R., Carlson, W.C., and Morgan, P. 1990. The target seedling concept. *In: Proc.Combined Meeting of the Western Forest Nursery Associations*. Rose, R., Cambell, S.J., and Landis, T.D. (eds.). USDA For. Serv. Gen. Tech. Rep. pp 1-8.

Roussos, P.A., Denaxa, N.K. Damvakaris, T., Stournaras, V., and Argyrokastritis, I. 2010. Effect of alleviating products with different mode of action on physiology and yield of olive under drought. Sci. Hortic., 125: 700-711.

Saraswathi, S.G. 2011. Drought induced changes in growth, leaf gas exchange and biomass production in *Albizia lebbeck* and *Cassia siamea* seedlings. J. Environ. Biol., 32: 173-178.

Saverimuttu, T. and Westoby, M. 1996. Seed longevity under deep shade in relation to seed size. J. Ecol., 84: 661-689.

Saxena, K.G., Rao, K.S., Sen, K.K., Maikhuri, R.K., and Semwal, R.L. 2001. Integrated natural resource management: approaches and lessons from the Himalaya. Conserv. Ecol., 15 (2): 5.

Saxena, R. and Nautiyal, S. 2001. Variation in growth and survival of five seed-sources of *Pinus roxburghii* sarg. under various stages of water stress. Indian For., 127 (5): 563-574.

Schumacher, E., Kuffer, C., Edwards, P.J., and Dietz, H. 2009. Influence of light and nutrient conditions on seedling growth of native and invasive trees in the Seychelles. Biol. Invasions, 11: 1941-1954.

Sela, E., Cohen, Y., Alchanatis, V., Moller, M., Meron, M., Saranga, Y., Cohen, S., Bosak, A., Tsipris, J., and Orolov, V. 2007. *In: Proc 6th Eur. Conf. Precision*

Agric. Stafford, J.V. (ed.). Wageningen Academic Publications, Netherlands, pp 365-371.

Shao, H.B., Chu, L.Y. Shao, M.A., Jaleel C.A., and Hong-Mei, M. 2008. Higher plant antioxidants and redox signaling under environmental stresses. Comptes Rendus Soc. de Biol., 331: 433-441.

Silva, B.T.V.B. and Ramana, R. 2005. The CWSI variations of a cotton crop in a semi-arid region of Northeast Brazil. J. Arid Environ., 62 (4): 649-659.

Singh, G. and Singh, B. 2009. Effect of varying soil water stress regimes on nutrient uptake and biomass production in *Dalbergia sissoo* seedlings in Indian desert. J. For. Res., 20 (4): 307-313.

Singh, J.S. and Singh, S.P. 1987. Forest vegetation of the Himalaya. Bot. Rev., 53: 80-192.

Smit, J. and Driessche, R. 1992. Root growth and water use efficiency of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and lodgepole pine (*Pinus contorta* Dougl.) seedlings. Tree Physiol., 11: 401-410.

Snyder, K.A. and Williams, D.G. 2007. Root allocation and water uptake patterns in riparian tree saplings: Responses to irrigation and defoliation. For. Ecol. Manage., 246: 222-231.

Souch, C.A. and Stephens, W. 1998. Growth, productivity and water use in three hybrid poplar clones. Tree Physiol., 18: 829-835.

Stark, J.C. and Wright, J.L. 1985. Relationship between foliage temperature and water stress in potatoes. Am. Potato J., 62: 57-68.

Starner, W.J. and Hardley, H.H. 1967. Chlorophyll content of various strains of soybeans. Crop Sci., 5: 9-11.

Steele, D.D., Stegman, E.C., and Gregor, B.L. 1994. Field comparison of irrigation scheduling methods for corn. Trans. ASAE, 37 (4): 1197-1203.

Steele, D.D., Stegman, E.C., and Knighton, R.E. 2000. Irrigation management for corn in the Northern Great Plains, USA. Irrig. Sci., 19: 107-114.

Stockle, C.O. and Dugas, W.A. 1992. Evaluating canopy temperature-based indices for irrigation scheduling. Irrig. Sci., 13: 31-37.

Taiz, L. and Zeiger, E. (eds.). 2006. *Plant Physiology*. Sinauer Associates, Inc., USA, 764p.

Tang, A.C., Kawamitsu, Y., Kanechi, M., and Boyer, J.S. 2002. Photosynthetic oxygen-evolution at low water potential in leaf discs lacking an epidermis. Ann. Bot., 89: 861-870.

Tanner, C.B. 1963. Plant temperatures. Agron. J., 55: 210.

Testi, L., Goldhamer, D.A., Iniesta, F., and Salinas, M. 2008. Crop water stress index is a sensitive water stress indicator in pistachio trees. Irrig. Sci., 26: 395-405.

Tripathi, R.S. and Khan, M.L. 1990. Effects of seed weight and micro site characteristics on germination and seedling fitness in two species of Quercus in a subtropical wet hill forest. Oikos, 57: 289-296.

Tripathi, B.S. and Saxena, V.K. 1986. Plantation breeding for red rot resistance in sugarcane. Sugarcane, 5: 13-15.

Tuomela, K. 1996. Leaf water relations in six provenances of *Eucalyptus microtheca*: a greenhouse experiment. For. Ecol. Manage., 92: 1-10.

USGS. 2006. Science for a changing world, Water science for school: How much water is there on earth? United States Geological Survey . Available at.

http://www.ga.water.usgs.gov/edu/earthhowmuch.html. Accessed on 11 Dec. 2010.

Waldo, L.J. 2009. Soil moisture spatial variability under Florida ridge citrus tree canopies and identifying alternative methods of scheduling irrigation based on tree canopy stress. MSc Thesis. University of Florida, Gainesville.

Walker, G.K. 1980. Relation between crop temperature and the growth and yield of kidney beans (*Phaseolus vulgaris* L.). Ph.D. Thesis. University of California, 203p.

Walker, G.K. and Hatfield, J.L. 1979. A test of the stress-degree-day concepr using multiple planting dates of red kidney beans. Agron. J., 71: 967-971.

Wallace, R. and Clum, H. 1938. Leaf temperatures. Am. J. Bot., 25: 83-97.

Wang, L.M, Qiu, G.Y., Zhang, X.Y., and Chen, S.Y. 2005. Application of a new method to evaluate crop water stress index. Irrig. Sci., 24: 49-54.

Wanjura, D.F. and Upchurch, D.R. 2000. Canopy temperature characterizations of corn and cotton water status. Trans. ASAE, 43: 867-875.

Wanjura, D.F., Kelly, C.A., Wendt, C.W., and Hatfield, J.L. 1984. Canopy temperature and water stress of cotton crops with complete and partial ground cover. Irrig. Sci., 5: 37-46.

Wanjura, D.F., Kelly, C.A., Wendt, C.W., and Hatfield, J.L. 1984. Canopy temperature and water stress of cotton crops with complete and partial ground cover. Irrig. Sci., 5: 37-46.

Waring, R. H. and Schlesinger, W. H.1985. *Forest Ecosystem: Concepts and Management*. Academic Press. Orlando, Florida, U.S, 338p.

Waring, R.H. 1991. Responses of evergreen trees to multiple stresses. In: *Response of plants to multiple stresses.* Mooney, H.A., Winner, W.E., and Pell, E.J. (eds.). Academic Press, Inc., New York, USA, pp. 371-390.

Webb, D.B., Wood, P.J., Smith, J.P., and Henman, G.S. 1984. A Guide to Species Selection for Tropical and Sub-Tropical Plantations. Trop. For. Pap. No. 15. Commonwealth Forestry Institute, Oxford, UK, 256 p.

Wen-zhong, Z., Yadong, H., and Hongjuan, D. 2007. Relationship between canopy temperature at flowering stage and soil water content, yield components in rice. Rice Sci., 14 (1): 67-70.

White, D.A., Beadle, C.L., and Worledge, D. 1996. Leaf water relations of *Eucalyptus globulus* and *E. nitens*: seasonal, drought and species effects. Tree Physiol., 16: 469-476.

White, D.A., Beadle, C.L., and Worledge, D. 2000. Control of transpiration in an irrigated *Eucalyptus globulus* Labill. plantation. Plant Cell Environ., 23: 123- 134.

Wilson, K.B., Baldocchi, D.D., and Hanson, P.J. 2001. Leaf age affects the seasonal pattern of photosynthetic capacity and net ecosystem exchange of carbon in a deciduous forest. Plant Cell Environ., 24: 571- 583.

Wu, Q.S., Xia, R.X., and Zou, Y.N. 2008. Improved soil structure and citrus growth after inoculation with three arbuscular mycorrhizal fungi under drought stress. Eur. J. Soil Biol., 44: 122-128.

Xiao, X., Boles, S., Liu, J., Zhuang, D., Frolking, S., Li, C., Salas, W., and Moore, B. 2005. Mapping paddy rice agriculture in southern China using multi-temporal MODIS images, Remote Sensing Environ., 95: 480-492.

Xiloyannis, C., Dichio, B., Nuzzo, V., and Celano, G. 1999. Defense strategies of olive against water stress. Acta Hort., 474: 423-426.

Yanbao, L., Chunying, Y., and Chunyang, L. 2006. Differences in some morphological, physiological and biochemical responses to drought stress in two contrasting populations of *Populus przewalski*. Physiol. Plant., 127: 182- 191.

Yazar, A., Howell, T.A., Dusek, D.A., and Copeland, K.S. 1999. Evaluation of crop water stress index for LEPA irrigated corn. Irrig. Sci.,18: 171-180.

Yuan, G.F., Luo, Y., Sun, X.M., and Tang, D.Y. 2004. Evaluation of crop water stress index for detecting water stress in winter wheat in the North China Plain. Agric. Water Manage., 64: 29-40.

Zainudin, S.R., Awang, K., and Hanif, A.H.M. 2003. Effects of combined nutrient and water stress on the growth of *Hopea odorata* Roxb. and *Mimusops elengi* Linn. Seedlings. J. Arboriculture, 29 (2): 79-83.

Zhang, R.S., Shen, Y.M., Lu, L.Y., Yan, S.G., Wang, Y.H., Li, J.L., and Zhang, Z.L. 2004. Formation of *Spartina alterniflora* salt marshes on the coast of Jiangsu Province, China, Ecol. Engng., 23: 95-105.

Zhen-hua, Z., Huanjie, C., and Runya, Y. 2005. Cotton yield estimation model based on crop water production function and CWSI. J. Agric. For., 12: 24-28.

Zhu, J.K. 2002. Salt and drought stress signal transduction in plants. Ann. Rev. Plant Biol., 53: 247-273.

MODELING CROP WATER STRESS INDEX (CWSI) IN TREE SEEDLINGS

By

SNEHA, C.
(2009-17-101)

ABSTRACT OF THE THESIS

Submitted in partial fulfilment of the

requirement for the degree of

Master of Science in Forestry

Faculty of Forestry

Kerala Agricultural University

DEPARTMENT OF TREE PHYSIOLOGY AND BREEDING
COLLEGE OF FORESTRY
VELLANIKKARA, THRISSUR-680 656
KERALA, INDIA

2011

ABSTRACT

The research work on 'Modeling crop water stress index (CWSI) in tree seedlings' was taken up at Department of Tree Physiology and Breeding, College of Forestry during April 2010 to March 2011.

The objective of the study was to detect water stress in seedlings of teak and mahogany with the help of infrared thermometry by developing CWSI. Six month old seedlings were provided with four different irrigation treatments- irrigation at IW/ET=1, 0.6 and 0.3 on weekly interval and a control treatment was maintained with no irrigation (IW/ET=0). Plant canopy temperature was recorded on daily basis from each treatment using a hand held infrared thermometer (HTC IR-8811). The non-water-stressed baseline (NWSB), obtained from canopy air temperature deficit and vapour pressure deficit (VPD) in the well watered treatment (irrigation at 1.0 IW/ET) and water stressed baseline obtained from non irrigated IW/ET=0. For teak the lower baseline was determined as CATD = -1.01VPD+2.8 and the upper baseline equation was CATD = -0.05VPD+5.1. For mahogany, lower baseline equation was CATD = -0.25VPD-2.9 and the upper baseline equation was CATD = -0.01VPD+6.1. CWSI was calculated for each treatment using these baseline equations. The CWSI responded to irrigation events along the whole season, and clearly detected mild water stress, suggesting extreme sensitivity to variations in plant water status. Non irrigated IW/ET=0 showed a greater value for CWSI for all the time followed by treatment provided with irrigation at IW/ET=0.3 while the treatments with higher irrigation levels (IW/ET= 1 and 0.6) had lower CWSI values. It indicates that there is an increase in CWSI with time as available water in the soil decreased. It has been observed during the study that teak seedlings are more susceptible to water stress than mahogany. Observation on canopy air temperature deficit showed that, teak seedlings from all treatments maintained a constant canopy air temperature deficit all over the week. In mahogany, IW/ET=1 and IW/ET=0 maintained a constant canopy air temperature deficit, whereas, IW/ET=0.6 and IW/ET=0.3 showed a slow increase

prior to the next irrigation. This reveals a relatively higher water use of teak seedlings when compared to mahogany.

Well watered mahogany seedlings showed higher crude protein content compared to other treatments indicating a significant reduction in photosynthesis occurred during water stress. But for teak seedlings no difference was observed among different treatments. Chlorophyll content was found to be decreasing due to water stress in both species. Teak seedlings showed significant reduction in total height, collar diameter, number of leaves, shoot weight, root weight, shoot root length ratio and relative growth rate on the course of stress treatment whereas root length was increasing. Shoot root biomass ratio was found to be least affected due to different levels of irrigation treatment. In the case of mahogany, collar diameter, shoot root length ratio and relative growth rate were found to be decreasing due to water stress. Root length was found to be increasing due to water stress. Plants were able to maintain total height, total leaf number, shoot weight, root weight and shoot root biomass ratio unaffected even under irrigation at IW/ET=0.3 also. Comparison on growth characteristics and physiological parameters of two species- teak and mahogany by providing different levels of irrigation revealed that mahogany uses water more efficiently than teak seedlings. The present series of investigations indicate the scope of CWSI in early detection of crop water stress. As is easy to find out and less time consuming, CWSI has got an immense potential in irrigation scheduling as well as water management.