Quantifying water stress using crop water stress index in mahogany (*Swietenia macrophylla* King) seedlings

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The present study was made to quantify water stress in mahogany (*Swietenia macrophylla* King) seedlings using crop water stress index (CWSI). Seedlings were provided with four different levels of irrigation as treatments – irrigation at irrigation water (IW)/evapotranspiration (ET) = 1, 0.6 and 0.3 at weekly intervals and a control with no irrigation (IW/ET = 0). Canopy–air temperature difference (CATD) was recorded using an infrared thermometer. The non-water-stressed baseline (NWSB) was derived from CATD and vapour pressure deficit (VPD) in the well-watered treatment (irrigation at 1.0 IW/ET). The lower baseline equation for CATD was –0.25VPD – 2.9 and the upper baseline equation was –0.01VPD + 6.1. CWSI responded to irrigation events along the whole season and clearly detected mild water stress, suggesting extreme sensitivity to variations in plant water status. The present study reveals the potential of CWSI for early, non-destructive and less time-consuming estimation of water stress.

Keywords: Canopy air temperature difference, crop water stress index, mahogany, relative chlorophyll content.

ALMOST 60% of global freshwater usage is for irrigation[1]. In a seedling nursery, around 50% of the total budget is spent on water management and irrigation. Nevertheless, water stress is the most important among the environmental stresses[2] limiting plant growth and productivity. With increase in afforestation activities, sustainable forest nursery irrigation practices are catching research attention. A better understanding about abiotic stresses and resultant plant responses will help nursery managers avoid large-scale water wastage and other failures in planting programmes[3].

Canopy air temperature difference (CATD)[4] can provide a good measure of actual stress levels, which can be effectively used for irrigation scheduling. Crop-specific critical values of the crop water stress index (CWSI) in different climates and soils are frequently used in irrigation management. An actively transpiring leaf with no water stress is able to loose energy and lower the temperature than surrounding air due to evaporative cooling. 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, CATD gives an ideal representation of crop water stress levels.

Mahogany (*Swietenia macrophylla* King), a fast-growing timber species is widely preferred for plantation and afforestation in India. This species requires a relatively long nursery period lasting about a year. Nursery costs, especially on irrigation, can be reduced for this species by the determination of its optimal irrigation frequency and water requirement[5]. Though information on irrigation requirements of mahogany is lacking, it is known that irrigation and shade have a profound influence in mahogany nurseries[6]. The present study employed CWSI to predict water stress in mahogany seedlings and provides a method for early detection of water stress.

The experiment was carried out at College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur district, Kerala (10°31′N and 76°13′E, 22.25 m amsl) during 2010 and 2011. The study area enjoys a warm, humid, tropical climate with distinct summer and rainy seasons. The weather parameters of the area during the study period (September 2010–March 2011) were recorded from the agro-meteorology observatory (Table 1).

Six-month-old mahogany seedlings were raised in polythene bags and grown under a rainout shelter. Irrigation water (IW) was provided once every seven days. The daily evapotranspiration during the past seven days was calculated using FAO modified Penman's equation and summed up to obtain cumulative transpiration (ET) for that period. The three irrigation treatments were applied with irrigation water equivalent to 100% (IW/ET = 1), 60% (IW/ET = 0.6) and 30% (IW/ET = 0.3) of the cumulative evapotranspiration (Table 1). A control (IW/ET = 0) was maintained without any irrigation. 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. The other two treatments with different irrigation levels (IW/ET = 0.6 and 0.3) were designed to evaluate different threshold CWSI values for scheduling the irrigation.

Canopy temperature and the corresponding air temperature were measured using a hand-held infrared thermometer (Agri-Therm II 6110.4ZL). Temperature measurements were done between 11 am and 12 noon, when the differences in temperature between stressed and non-stressed crops are most readily detected[7]. Fifteen observations were recorded each day and tabulated for comparing treatment difference as well as influence of weekly irrigation. Relative humidity and air temperature were also recorded to calculate vapour pressure deficit (VPD) of air using the procedure given by Allen *et al*.[8].

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Table 1. Weather parameters recorded and cumulative evapotranspiration and VPD estimated during the study period (2010–11)

Month	Date	Temperature (°C)		RH (%)	SSH (h)	WS (km/h)	Cumulative ET (mm)	VPD (kPa)
		Maximum	Minimum					
September	7–13	29.8	23.4	84.6	1.9	2.2	21.7	3.96
	14–20	29.6	23.1	85.4	3.4	2.5	25.1	4.28
	21–28	31.5	22.7	82.4	3.4	2.4	29.5	5.36
September–October	29–5	32.0	22.9	80.3	6.6	2.5	34.1	6.06
	6–12	28.8	23.2	87.1	3.5	1.7	25.1	3.80
	13–19	29.4	22.1	84.3	4.8	2.1	28.1	4.42
	20–26	29.5	22.4	85.1	5.0	2.2	28.4	4.37
October–November	27–2	30.1	21.9	84.8	2.8	2.4	23.0	4.55
	3–9	30.3	22.6	82.1	4.9	2.2	28.4	5.25
	10–16	31.6	22.5	80.4	6.8	2.4	32.9	6.03
	17–23	30.9	22.4	80.3	3.9	3.4	25.7	5.81
	24–30	28.9	22.6	78.9	1.7	6.1	20.7	5.44
December	1–7	30.7	21.9	74.1	3.8	3.9	25.7	6.61
	8–14	31.2	21.2	76.3	6.4	2.4	30.9	6.02
	15–21	30.9	23.1	68.2	7.8	7.0	34.7	7.63
	22–28	30.8	21.1	63.6	8.9	6.4	36.8	8.16
December–January	29–4	31.4	22.4	67.1	6.6	4.6	32.5	7.68
	5–11	32.9	23.3	67.5	6.4	3.9	33.1	7.55
	12–18	32.7	21.4	56.3	8.4	5.4	37.3	7.65
	19–25	32.4	21.2	50.1	10.0	8.4	39.1	7.88
January–February	26–1	33.4	23.6	50.3	9.8	9.5	39.4	10.45
	2–8	33.6	21.3	45.8	9.1	6.2	37.0	11.80
	9–15	34.3	21.4	44.9	10.0	6.4	38.9	11.68
	16–22	33.5	21.7	71.0	8.2	3.3	35.8	6.23
February–March	23–1	33.3	23.6	67.6	6.5	4.6	33.8	7.18
	2–8	35.8	23.0	52.6	10.0	4.6	40.9	10.43
	9–15	35.1	23.6	68.0	9.2	3.9	39.8	6.05
	16–22	34.6	23.8	61.0	8.7	4.6	38.0	7.31
	23–29	33.8	25.2	73.5	6.7	3.2	33.9	5.39

RH, Relative humidity, SSH, Sunshine hours; WS, Wind speed; ET, Evapotranspiration; VPD, Vapour pressure deficit.

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 was thus developed from the scatter diagram by linear regression technique. CWSI was calculated separately for each treatment using the following equation[9].

$$\mathrm{CWSI} = \frac{(T_\mathrm{c} - T_\mathrm{a}) - (T_\mathrm{c} - T_\mathrm{a})_{ll}}{(T_\mathrm{c} - T_\mathrm{a})_{ul} - (T_\mathrm{c} - T_\mathrm{a})_{ll}},$$

where T_c is the canopy temperature, T_a the air temperature, *ll* the non-water-stressed baseline and *ul* the non-transpiring upper baseline.

In order to estimate the efficiency of CWSI in determining water stress in seedlings, chlorophyll content (using chlorophyll meter SPAD-502, Minolta), seedling height and collar diameter were measured. Ten randomly selected, mature leaves were used for estimation of chlorophyll content. Observations on seedling height and collar diameter were taken from five randomly selected seedlings.

CATD of IW/ET = 0 and IW/ET = 0.3 was positive, whereas for well-watered treatments (IW/ET = 1 and 0.6), CATD remained negative (Table 2). This implies that treatments IW/ET = 0 and IW/ET = 0.3 were under water stress throughout the growing period, whereas IW/ET = 1 and 0.6 were not. Irrigation at levels IW/ET= 1 and 0.6 was sufficient for the evaporative demand of mahogany seedlings. No significant difference was observed among mahogany seedlings of treatments IW/ET = 1 and 0.6 in CATD, which implies that even the level of irrigation in the treatment IW/ET = 0.6 is enough for the plants to maintain normal canopy temperature. Performance of treatment IW/ET = 0.3 was found to be lower than that of IW/ET = 0 up to the sixth day but increased and remained on par with IW/ET = 0 on the seventh day. This increase in CATD might be due to complete depletion of soil water on the seventh day after irrigation. CATD of treatments IW/ET = 1 and IW/ET = 0 remained without any significant difference throughout the week. In IW/ET = 1, no significant variation was observed in CATD, which may be due to availability of sufficient amount of water at all times. In the case of

Table 2. Canopy air temperature difference of mahogany seedlings in response to different irrigation levels (°C)

	Days after irrigation							
Treatment	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	SEm ±
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 ±	4.6*	4.2*	3.8*	3.7*	4.1*	4.2*	4.7*	

*Significant at 5%; Values with similar superscripts along the column do not differ; ns, Non-significant at 5%.

Table 3. Seedling height, collar diameter and chlorophyll content of mahogany seedlings after six months

Treatment	Mean seedling height (cm)	Collar diameter (mm)	Chlorophyll content (mg/g)
IW/ET = 1	109.7	10.9^{a}	0.51^{a}
IW/ET = 0.6	101.4	10.4^{a}	0.48^{a}
IW/ET = 0.3	102.3	8.3^{b}	0.37^{b}
IW/ET = 0	–	–	–
SEm ±	7.9^{ns}	0.7*	0.06*

*Significant at 5%; Values with same superscript do not differ; ns, Non-significant at 5% level.

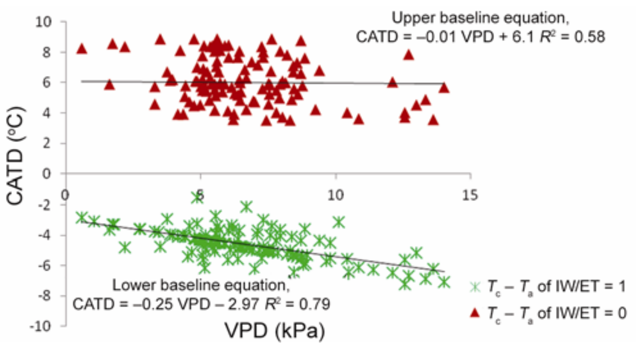

Figure 1. Upper and lower baseline for canopy air temperature difference in mahogany.

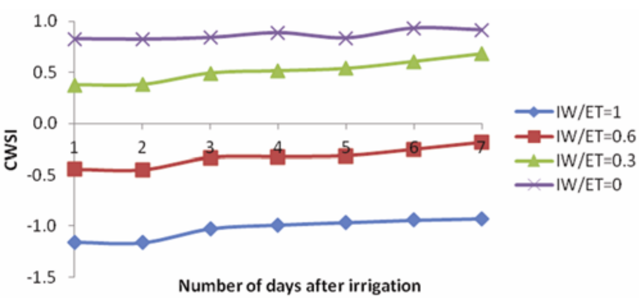

Figure 2. Crop water stress index in mahogany seedlings over a week.

treatment IW/ET = 0, the plants maintained almost steady CATD which might be due to their ability to acclimate with water stress. Significant increase in CATD of IW/ET = 0.6 and IW/ET = 0.3 might be due to periodical depletion of soil water and reduced evapotranspiration in the course of time after irrigation.

Lower baseline equation for CATD was determined as –0.25VPD – 2.9 and upper baseline equation was CATD –0.01VPD + 6.1 (Figure 1). Jackson *et al.*[10] 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, so that even a mild water-stress will not affect the productivity of plants.

In theory, CWSI should progress from zero for non-stressed plants transpiring at potential rates, to 1 for severely stressed plants that are not transpiring[9]. In the present study, it was found that the value of CWSI exceeded the expected limits. In treatment IW/ET = 1, CWSI ranged from –1.9 to –0.4 and in IW/ET = 0.6, it was from –1.2 to 0.3. In treatments IW/ET = 0 and IW/ET = 0.3, CWSI remained positive all the time (Figure 2) and sometimes exceeded the theoretically maximum limit of '1'. Occurrence of negative values and values greater than 1 has been presented in many other studies[11–14], which 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. According to Jones[15,16], CWSI has not been used in all climates as it will not be accurate, especially under humid conditions. In order to check this 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 crop root zone was depleted. But CWSI of IW/ET = 0 remained without much fluctuation all the time.

In order to estimate the efficiency of CWSI in determining water stress in seedlings, other parameters like total chlorophyll content, seedling height and collar diameter also were measured (Table 3).

In well-watered treatments IW/ET = 1 and IW/ET = 0.6, chlorophyll content was higher and on par. Significant reduction in chlorophyll content was observed in treatment IW/ET = 0.3. 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[17,18]. Many of the existing reports suggest that mild stress will not affect chlorophyll content[19–21]. So it can be assumed that irrigation at IW/ET = 0.3 imposes severe stress in mahogany seedlings affecting chlorophyll content.

Seedling height was not influenced by the irrigation treatments applied in the experiment. 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 (102.3 cm) and IW/ET = 0.6 (101.4 cm).

Mahogany seedlings showed significant difference in collar diameter due to different irrigation treatments. Least irrigated (IW/ET = 0.3) seedlings showed reduction in collar diameter compared to the well-watered treatments. 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.

These results suggest that CWSI has 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. The influence of other weather parameters like relative humidity, wind speed and soil physical properties on CWSI can also be investigated.

In conclusion, the effectiveness of CWSI for early detection of water stress in mahogany seedlings was monitored. Six-month-old seedlings were used for this study. Effect of different levels of irrigation on plant canopy temperature was assessed using an infrared thermometer by developing CWSI. Physiological as well as biometric parameters were also recorded. It has been observed that CWSI has immense potential for early non-destructive estimation of water stress in plants. Baselines for upper and lower canopy temperature were also developed which can be used in the nursery for irrigation scheduling. It was found that irrigation at IW/ET = 0.6 is as good as IW/ET = 1, whereas water supply at IW/ET = 0.3 is not sufficient to meet the water requirements of mahogany seedlings.

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