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Irrigation requirement of rubber trees (*Hevea brasiliensis*) in the subhumid tropics

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Abstract

North Konkan region in the west coast of India is only marginally suitable for rubber (*Hevea brasiliensis*) cultivation due to subhumid climate. The region has a rainless period with severe soil moisture deficits in summer. Heavy leaf injury and shedding is experienced in summer months. The immaturity period of the crop, attainment of 50 cm girth by main trunk, in the region under rainfed conditions is very long extending to more than 10 yrs. An irrigation experiment was laid out to quantify the requirement of irrigation water and for comparative evaluation of basin and drip irrigation systems. In the experimental site, the drip irrigation was inferior to basin irrigation. Growth rates achieved under irrigation regimes of 1.00 crop evapotranspiration (ET_c) and 0.50 ET_c were comparable suggesting that only 50% of the estimated crop water requirement for the summer season is the irrigation requirement. The immaturity period could be reduced to 6 yrs by irrigation. Sufficient irrigation was found to eliminate foliar injury and to result in a high photosynthetic rate. Path coefficient analysis revealed that photosynthetic rate, leaf area index, turgor pressure and leaf temperature have direct and positive relationship with the fortnightly relative growth rate. The results of path coefficient analysis of photosynthetic rate with physiological factors revealed that latex solute potential is the major parameter affecting the photosynthetic rate under stress conditions. Other parameters namely, leaf epicuticular wax, turgor pressure, stomatal resistance and chlorophyll indirectly affect photosynthesis. © 1998 Elsevier Science B.V.

Keywords: Hevea brasiliensis; Soil moisture stress; Plant water status; Basin irrigation; Drip irrigation; Photosynthesis; Crop coefficient; Rubber; Water use efficiency; Irrigation water requirement

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1. Introduction

Plantations of rubber (*Hevea brasiliensis*) are traditionally raised under rainfed conditions except in nurseries where essential irrigation is given. Ideally, monthly rainfall should be sufficient to meet the water requirements of the plantation. In the tropical monsoon climate, the potential evapotranspiration rate is around 4 mm day^{-1} (Montieth, 1977) and rainfall of 125 mm month^{-1} evenly distributed through the year is considered essential to maintain optimum gaseous exchange (Sanjeeva Rao and Vijayakumar, 1992). The traditional region of rubber cultivation in India is the southern part of the west coast extending from Kanyakumari (8°15′N) to Mangalore (12°52′N). In spite of moderate water stress in summer, this region is considered the most suitable for rubber cultivation in India (Vijayakumar et al., 1988).

Now attempts are being made to extend cultivation of rubber up to the North Konkan region (20°N) of the West Coast. In this region, the climate is subhumid and is only marginally suitable for *H. brasiliensis* cultivation because of a prolonged dry season and high temperatures in summer (Vijayakumar et al., 1988; Mohankrishna et al., 1991). The mean annual rainfall of 2175 mm is concentrated between June and September and the annual potential evapotranspiration is 2250 mm. Initial rains from the southwest monsoon during June contribute towards recharge of the soil. Rainfall received in July is 1000 mm and is less in subsequent months. Topography of the land is undulating with small hillocks and is generally classified into uplands and lowlands. Upland soil in the region is oxisol with pH 6.3 (Karthikakuttyamma et al., 1989). The high intensity of rainfall results in surface runoff and the high volume in deep percolation losses of water. During October and November, stored soil moisture fulfills the water requirement of the plants. Plants, however, experience stress conditions from December onwards as soil moisture becomes depleted, reaching below permanent wilting point (PWP) in the upper layers (0–60 cm) during March to May (Mohankrishna et al., 1991). The region experiences a cumulative water deficit of 1168 mm during summer months. Thus climatic conditions are highly unfavourable for cultivation of rubber.

Severe growth reduction and longer immaturity periods have been reported (Chandrashekar et al., 1990; Mohankrishna et al., 1991; Chandrashekar et al., 1994; Rubber Research Institute of India, 1995–1996). While time taken to attain tappable girth by the trunk (50 cm girth at 125 cm above bud union) is usually 6–7 yrs in the southern part of the west coast, it is more than 10 yrs in North Konkan (Rubber Research Institute of India, 1993–1994). Mohankrishna et al. (1991) have quantified stomatal closure and simultaneous reduction in CO_2 assimilation and transpiration in rainfed and irrigated young *H. brasiliensis* plants in the region.

Evapotranspiration depends on the microclimate and leaf area of the canopy. Physiological status of plants under water stress is the major indicator of the extent of stress experienced. Chandrashekar et al. (1990) reported extreme reductions in plant moisture status and stomatal conductance in mature *H. brasiliensis* in the region during summer. An experiment was laid out in the North Konkan region in 1987 with the objective of quantifying the requirement of irrigation water and for comparative evaluation of basin and drip irrigation methods. Studies on physiological changes under different moisture regimes were also envisaged. Results of the study in the initial years (1987–1990) were reported by Mohankrishna et al. (1991). Results of the subsequent years are reported in this paper.

2. Materials and methods

An experiment was laid out in 1987 in the Rubber Research Institute of India's Regional Research Station at Dapchari (20°4′N, 72°4′E, 48 m MSL). The experimental field has a gentle slope. The soil type is an oxisol with pH 6.3, bulk density 1.4 Mg m^{-3}, field capacity 30.5% and permanent wilting point 17.2% (gravimetric estimations). Layout of the experiment is a randomised block design with three replications comprising 25 plants per plot (600.25 m^{-2}) in square planting at 4.9 m × 4.9 m spacing with an effective population of 400 trees ha^{-1}. Young budded plants of clone RRII 105 raised in polythene baskets for 9 months were used as planting material. The plants were raised following cultural practices recommended for the traditional rubber-growing region.

For imposing irrigation treatments, crop evapotranspiration (ET_c), and thus the quantity of irrigation water per plant per irrigation and scheduling of irrigation were estimated following assumptions made by Vijayakumar et al. (1988) for *H. brasiliensis* in the humid tropics of India (rooting depth = 0.5 m; canopy coverage = 10–90% from first to seventh year; basin area = 1.6 to 3.4 m^2; crop coefficient = 1.0; depletion of soil moisture for 1.0 ET_c schedule 50% available soil moisture) and using meteorological data generated in the station from 1985 onwards. Potential evapotranspiration (PET) values were estimated by modified Penman equation as suggested by Rao et al. (1971) for Indian conditions. The modifications are mainly related to corrections for elevation by considering station-level pressure and incoming radiation using latitude of the station. Up to 1991, the assumed crop coefficient was 1.00. Since water stress was observed even in plants irrigated at the rate of 1.00 ET_c (Mohankrishna et al., 1991), it was revised to 1.25 from 1992 onwards. Assumptions on canopy coverage were also revised at that time. It was assumed to increase from 10% in the first year to 90% in the fifth year without any further increase. Rooting depth was assumed to be 0.7 m. Basin area was 2.5 m^2, in the first 2 yrs, 3.4 m^2 in the third year, 6.25 m^2 during the fourth year and 6.5 m^2 during subsequent years. Quantity of water per irrigation was 150 l $plant^{-1}$ during the first 2 yrs, 212 l in the third year, 400 l in the fourth year and 420 l during subsequent years.

Treatments comprise control (T1, no irrigation), three levels of basin irrigation (T2, 0.50; T3, 0.75; and T4, 1.00 ET_c) and three levels of drip irrigation (T5, 0.25; T6, 0.50; and T7, 0.75 ET_c). Number of irrigations scheduled and given in 1991, 1992 and 1993 are presented in Table 1. For drip irrigation, pressure-compensated emitters were used. Two emitters of 2 l hr^{-1} capacity for trees under 0.25 ET_c, 4 emitters of 2 l hr^{-1} capacity for trees under ET_c 0.50 treatment and 3 emitters of 4 l hr^{-1} capacity for trees under 0.75 ET_c were installed in the basins. The basins were covered with heavy organic mulch. The fertilizer applied comprised NPK in the form of urea, rock phosphate and muriate of potash at the rates of 22.5, 22.5 and 11.4; 90.0, 90.0 and 36.0; 110.0, 110.0 and 44.0; 90.0, 90.0 and 36.0 g $plant^{-1}$, respectively during the first, second, third and fourth years. From fifth year onwards, till the commencement of tapping, the amounts of

Table 1
Number of irrigations given and scheduled (in parenthesis) in different basin treatments

Month	ET_c treatments	Number of irrigations given		
		1991	1992	1993
December	0.50	–	–	5 (5)[a]
	0.75	–	–	7 (7)[a]
	1.00	–	–	10 (10)[a]
January	0.50	2 (2)	4 (5)	5 (5)
	0.75	3 (3)	6 (8)	8 (8)
	1.00	4 (4)	9 (11)	10 (11)
February	0.50	3 (3)	4 (6)	6 (6)
	0.75	3 (4)	5 (9)	9 (9)
	1.00	6 (6)	6 (12)	12 (12)
March	0.50	4 (4)	7 (8)	5 (8)
	0.75	5 (5)	9 (11)	9 (11)
	1.00	6 (7)	14 (15)	13 (15)
April	0.50	3 (3)	8 (8)	8 (8)
	0.75	6 (6)	12 (12)	11 (12)
	1.00	8 (8)	16 (16)	13 (16)
May	0.50	3 (4)	6 (7)	7 (7)
	0.75	5 (6)	9 (12)	12 (12)
	1.00	5 (7)	12 (16)	16 (16)
June	0.50	1	7	2
	0.75	–	5	4
	1.00	1	5	5

[a] December 1992.

NPK given were respectively 75.0, 75.0 and 75.0 g plant^{-1}. The fertilizer applications were made inside the basins in two splits during June and September. In the first year the entire fertilizer was given in one dose during September. From third year onwards 25% of the recommended dose of fertilizer was given as an additional dose to all the irrigated plants in February.

Girth of the trunk at 1.5 m above the bud union was recorded at 15-day intervals. In each plot, observations were recorded in nine plants after excluding the border plants. Biomass was estimated from girth by using Eq. (1),

$$\text{Biomass (kg)} = 0.0026 G^{2.78} \quad (1)$$

(where G is girth in cm) developed by Shorrocks et al. (1965). Relative growth rate (RGR) was calculated from biomass changes. Final biomass of the rainfed plants was found to be a function of initial biomass and quantity of water received. These two effects were isolated by developing a regression equation using growth data of rainfed plants,

$$Y = 15.18 + 1.01 X \quad (2)$$

where X is the initial biomass and Y is the expected final biomass under rainfed conditions. Possible growth of the irrigated plants if they were under rainfed condition could be estimated using Eq. (2). Growth due to irrigation alone was derived by deducting the predicted rainfed growth from the actual growth under irrigation. Water use efficiency (WUE) was calculated by dividing the biomass increment due to irrigation with the quantity of water applied.

Physiological parameters, reported here, were recorded during the second and third weeks of May 1993, three weeks before the onset of monsoon. One plant from each plot was selected for observations on photosynthesis and other physiological parameters. Canopy area indices were measured by canopy analyzer (LI 2000, Licor, USA). Photosynthesis and associated characters were recorded using a portable photosynthesis system (LI 6200, Licor, USA) three times of a day at 8:00, 12:00 and 15:00 h in each treatment. Physiological parameters were measured from middle leaflet of one of the youngest fully mature flushes in each plant. Turgor pressure of latex vessels in the bark of the trunk, measured at 6:00, 12:00 and 15:00 h, was measured by a 0.2 m manometric tube (Raghavendra et al., 1984). For solute potential measurements, latex samples were extracted from the manometers after recording turgor pressure. Measurements were made using C52 sample chambers and HR 33 microvoltmeter (Wescor, USA) under psychrometric mode. Latex vessel water potential was worked out from latex solute potential and turgor pressure. Leaf surface wax content was determined by the gravimetric method (Ebercon et al., 1977). Injury to leaves was calculated by subtracting the green leaf area from total leaf area in 100 leaf samples collected from control plants. Total chlorophyll was estimated following the method of Arnon (1949). In the case of plants under basin irrigation, data on physiological parameters were collected on the day before irrigation. Soil samples were also collected on the same day for gravimetric estimation of moisture content.

Correlation and path coefficient analysis (standardised partial regression coefficient) were performed to understand the effect of physiological parameters on growth. The average value of the three recordings taken on each day of photosynthesis rate, stomatal resistance, turgor pressure and latex solute potential were used for path coefficient analysis. Percentage of tappable trees obtained for different treatments were analysed after subjecting the values to square root transformation (Steel and Torrie, 1980).

3. Results

3.1. Soil moisture content

Observations on soil moisture (data not presented) showed depletion to wilting point up to 0.6 m in the rainfed plots indicating deeper rooting depth. In the irrigated basins, it was much above wilting point and ranged from 21 to 26%.

3.2. Growth parameters

Data on girth, biomass produced and percentage of trees with tappable girth as in January 1994 and water use efficiency are presented in Table 2. Irrigation resulted in

Table 2
Effect of different irrigation treatments on girth increment, biomass production, percentage of tappable trees (January 1994) and water use efficiency in *H. brasiliensis*

ET_c treatments	Girth (cm)	Biomass (kg $tree^{-1}$)	Percentage of trees with tappable girth (Root transformed data)[2]	Water use efficiency ($g\ l^{-1} \pm SE$)
Control	34.3 c	49 d	0.71 c (0.0)	–
0.50 basin	46.6 ab	113 abc	2.84 bc (12.0)	1.14 ± 0.07
0.75 basin	49.5 a	134 ab	7.05 a (50.0)	1.08 ± 0.05
1.00 basin	49.9 a	137 a	7.30 a (53.6)	0.84 ± 0.05
0.25 drip	41.6 b	83 c	1.69 c (3.2)	1.23 ± 0.22
0.50 drip	45.0 ab	103 bc	1.44 c (1.6)	1.13 ± 0.05
0.75 drip	46.3 ab	111 abc	4.43 b (20.0)	0.93 ± 0.07
CD (0.01)	5.3	30	2.36	–

[a] Values in parenthesis are percentage of trees with tappable girth.
Means not followed by same letters are significantly different at $P < 0.01$.

highly significant increase in growth. By January 1994, the biomass of irrigated plants (1.00 and 0.75 ET_c basin) was 2.8 times more than those of the rainfed plants. Growth performance under all irrigation treatments except 0.25 ET_c were similar. Though statistically nonsignificant, growth under 0.50 and 0.75 ET_c drip irrigation regimes were less compared to growth under the respective basin irrigation treatments. More than 50% of the trees under 0.75 ET_c and 1.00 ET_c basin irrigation treatments attained tappable girth by January 1994. In the other treatments, the percentage was significantly lower. In general, growth performance was better under basin irrigation treatments. Water use efficiency (Table 2) in terms of dry matter produced per unit of water applied showed negative relation with quantity of water applied. It ranged from 0.84 to 1.23 g l^{-1}.

Seasonal changes in RGR of plants under different treatments for the period from 1990 to 1993 are given in Table 3. Fortnightly changes in RGR under rainfed and basin irrigation treatments from January 1993 to November 1993 are presented in Fig. 1. Irrigated plants showed considerable growth in the summer months. However, the

Table 3
Relative growth rate during dry seasons under different irrigation treatments

ET_c treatments	Relative growth rate (g kg^{-1} $month^{-1}$)			
	1990	1991	1992	1993
Control	2.9 (2)	1.1 (10)	0.2 (0.3)	1.4 (2)
0.50 basin	37.8 (29)	69.3 (58)	44.3 (62)	34.8 (63)
0.75 basin	54.9 (39)	81.9 (82)	68.6 (107)	44.8 (79)
1.00 basin	65.0 (40)	89.9 (92)	75.1 (117)	50.2 (92)
0.25 drip	24.6 (14)	77.9 (63)	28.5 (41)	12.4 (18)
0.50 drip	22.8 (12)	88.6 (73)	46.8 (65)	33.4 (52)
0.75 drip	53.1 (29)	102.8 (86)	54.4 (73)	43.4 (66)
CD (0.05)	7.8	19.2	13.2	9.9

Figures in parentheses are the percentage of wet season RGR.

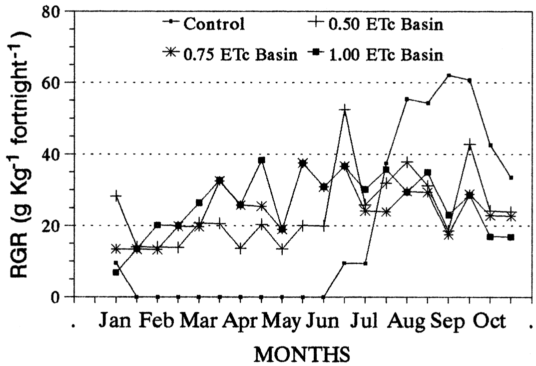

Fig. 1. Fortnightly relative growth rates (RGR) of *H. brasiliensis* under different irrigation treatments during January 1993 to October 1993.

rainfed plants showed only negligible growth until the end of July even though rain had started in the middle of June. In the subsequent months of the wet season, RGR of the rainfed plants was more than that of the irrigated plants. The same pattern was also observed in the earlier years. In the 1992 dry season, basin irrigation at the rates of 0.75 and 1.00 ET_c resulted in better mean RGR than was achieved during the previous wet season. However, this superiority was not observed in the dry season of 1993. During this season basin irrigation at the rate of 1.00 ET_c resulted in achieving only 92% of the previous wet season mean RGR recorded in the same plants.

3.3. Leaf area and other characters

Data on leaf area index, chlorophyll, leaf surface wax content and leaf temperature are presented in Table 4. Rainfed plants showed repeated defoliation and refoliation in the dry season. Leaves which did not abscise showed injury as severe yellowing and margin drying. Chlorophyll loss was 75% and margin drying was 35%. Such symptoms

Table 4
Effect of different irrigation treatments on leaf area index (LAI), total chlorophyll, leaf temperature (12.00 h) and leaf epicuticular wax in *H. brasiliensis* in May 1993

Et_c treatments	LAI	Total chlorophyll (mg dm^{-2})	leaf *T* (°C)	Leaf epicuticular wax (μg cm^{-2})
Control	0.93	1.10	45.0	155
0.50 basin	3.75	4.18	41.0	113
0.75 basin	4.36	4.09	41.1	108
1.00 basin	4.40	4.90	40.8	92
0.25 drip	3.02	3.81	41.8	125
0.50 drip	3.52	3.97	40.3	120
0.75 drip	4.34	4.19	40.8	98
CD (0.05)	0.56	0.97	1.23	8.8

were absent in fully irrigated plants (1.00 ET_c). In the rainfed plants, reduction in leaf area index was 79%. Mild symptoms of stress, but not leaf margin drying, were observed in partially irrigated plants. Increased leaf surface wax content and leaf temperature were also observed in rainfed and partially irrigated plants.

3.4. Photosynthesis and associated characters

Photosynthetic rate, Pn, stomatal resistance and transpiration rate at different times of the day are presented in Table 5. Photosynthetic rate showed variation during the day and among the treatments. Compared to 12:00 and 15:00 h, Pn was higher at 8:00 h. In plants receiving 1.00 ET_c basin and 0.75 ET_c drip irrigation treatments, the values were respectively 18.2 and 17.8 μmol m^{-2} s^{-1} whereas it was only 4.3 μmol m^{-2} s^{-1} in the rainfed plants. Photosynthetic rate in plants under 1.00 ET_c basin and 0.75 ET_c drip were comparable. In the other treatments, the rates were significantly reduced. Midday and afternoon depressions in Pn were larger in the basin-irrigated plants compared to plants under drip irrigation. However, in plants receiving basin irrigation at the rate of 0.75 and 1.00 ET_c, there was considerable increase in CO_2 assimilation rates in the afternoon hours, the values being comparable to those of the drip-irrigated plants (0.75 ET_c).

Stomatal resistance was high in control plants even at 8:00 h (Table 5). Plants receiving 0.25 ET_c drip irrigation also showed a severe degree of stomatal closure at this time. Low values of stomatal resistance were recorded in plants under higher water regimes. In the midday and afternoon hours there was marked increase in stomatal resistance in the rainfed plants and in plants receiving lower quantities of water. In plants receiving 1.00 ET_c basin, 0.75 drip and 0.50 drip irrigation regimes increase in stomatal resistance was only moderate at 12:00 h and showed decline at 15:00 h except in plants under 0.50 ET_c drip irrigation. In plants under 0.75 and 1.00 ET_c, transpiration rates showed steady increase up to 15:00 h, while in plants which received lower quantities of irrigation water there was reduction in transpiration at this time.

Table 5
Effect of different irrigation treatments on net photosynthetic rate, stomatal resistance and transpiration rate at different times of day in *H. brasiliensis*

ET_c treatments	Photosynthetic (μmoles m^{-2} s^{-1})			Stomatal resistance (s cm^{-1})			Transpiration rate (mmoles m^{-2} s^{-1})		
	8:00 h	12:00 h	15:00 h	8:00 h	12:00 h	15:00 h	8:00 h	12:00 h	15:00 h
Control	4.3	0.3	0.4	6.5	10.1	37.6	4.8	6.4	1.8
0.50 basin	15.6	3.4	3.9	1.8	5.2	7.0	11.0	10.0	7.3
0.75 basin	15.6	6.5	10.4	2.1	2.7	2.1	9.8	13.3	16.4
1.00 basin	18.1	7.0	11.3	1.3	2.3	1.9	13.3	17.9	18.9
0.25 drip	11.3	2.8	3.0	3.1	7.9	13.2	7.0	6.9	5.2
0.50 drip	14.7	6.7	7.4	1.9	2.7	3.2	7.6	13.5	13.0
0.75 drip	17.8	10.4	10.5	1.6	2.2	1.7	11.1	16.5	19.6
CD (0.05)	1.6	2.0	2.0	0.9	1.8	7.9	1.0	3.6	3.5

Table 6
Effect of different irrigation treatments on plant water status (turgor pressure, latex solute potential and latex vessel water potential) at different time of day in *H. brasiliensis*

ET_c treatment	Turgor pressure (MPa)			Latex solute potential (MPa)			Latex vessel water potential (MPa)		
	6:00 h	12:00 h	15:00 h	6:00 h	12:00 h	15:00 h	6:00 h	12:00 h	15:00 h
Control	0.22	0.10	0.10	−1.35	−1.95	−1.98	−1.13	−1.85	−1.88
0.50 basin	0.65	0.10	0.11	−1.10	−1.55	−1.73	−0.45	−1.45	−1.63
0.75 basin	0.81	0.12	0.13	−0.92	−1.33	−1.47	−0.11	−1.21	−1.34
1.00 basin	0.81	0.12	0.16	−0.92	−1.32	−1.47	−0.11	−1.20	−1.30
0.25 drip	0.64	0.10	0.10	−1.07	−1.62	−1.82	−0.43	−1.52	−1.72
0.50 drip	0.67	0.11	0.10	−0.95	−1.45	−1.50	−0.28	−1.34	−1.40
0.75 drip	0.73	0.13	0.11	−0.95	−1.45	−1.57	−0.22	−1.32	−1.46
CD (0.05)	0.17	ns	0.01	0.20	0.11	0.12	0.19	0.11	0.13

ns, not significant.

3.5. Latex vessel water relations

Data on latex vessel turgor pressure, latex osmotic potential and latex vessel water potential are presented in Table 6. Significant differences in turgor pressure (TP) were observed among the treatments. At 6:00 h, the TP was very low in the rainfed plants. Though TP of the irrigated plants showed increase with increase in quantity of irrigation, these were statistically nonsignificant. Mean TP was 0.65, 0.11 and 0.12 MPa at 6:00, 12:00 and 15:00 h, respectively. By midday the values dropped to around 0.10 MPa in all treatments and the differences were statistically not significant. At 15:00 h TP was very low in all the treatments. Signs of recovery was observed in plants under 1.00 and 0.75 ET_c basin irrigation regimes. Differences were also observed in latex solute potentials of plants under different treatments. Solute potential showed decreasing trend during the day time, the mean values being −1.04, −1.52 and −1.65 MPa, respectively at 6:00, 12:00 and 15:00 h. At 6:00 h the solute potential was considerably lower in the rainfed plants. Decline of osmotic potential during the course of the day was more pronounced in the plants without irrigation as well as in the plants which received lower amounts of water. Latex vessel water potential also followed similar trend to that of osmotic potential and showed significant differences among the treatments. The mean values were −0.39, −1.41 and −1.53 MPa at 6:00, 12:00 and 15:00 h, respectively. Values at 6:00 h indicated severe stress in plants without irrigation and moderate stress in plants receiving 0.50 ET_c basin and 0.25 ET_c drip irrigation treatments. Fall in latex vessel water potential during the day time was also more pronounced in these treatments.

4. Discussion

The results presented confirm the poor growth of rainfed *H. brasiliensis* in subhumid climate of the North Konkan region. Marked increase in growth could be achieved by irrigation, the biomass increase being 2.8 times. In plots under 0.75 and 1.00 ET_c basin irrigation regimes, more than 50% of the trees attained tappable girth, the standard set for commercial tapping, by January 1994. This growth duration is less than what is generally observed in the traditional region under rainfed conditions. A further reduction in the immaturity period would have been possible if the treatments were imposed from the beginning itself, based on the revised estimates of the water requirements and without the initial failures in implementing the scheduled irrigations (Mohankrishna et al., 1991). The study proves that the long immaturity period observed in the region under rainfed conditions can be overcome by irrigation. Irrigation brings about other advantages also. While tree loss was as high as 18% in the rainfed plots, it was only 3.7% in the irrigated plots. Variation in girth was more (12.5%) among rainfed plants than among irrigated plants (7.1%). Unlike in the traditional region (Vijayakumar et al., 1988), there is severe soil moisture depletion in the Konkan region during summer months (Chandrashekar et al., 1990, 1994). Soil moisture depletion observed in the control plots is in conformity with the earlier reports.

Studies on physiological parameters show that an increase of the crop coefficient to 1.25 is justified. This confirms higher water requirement of *H. brasiliensis*. In Malaysia, the daily ET rate of the clone RRIM 600 grown under glass house was found to vary from 2.1 to 6.9 mm d^{-1} (Haridas, 1980) and under field conditions this was found to be 4.4 mm d^{-1} when averaged over 21 months. In Ivory Coast, while measuring the energy balance components of a homogeneous plot of 25 ha with 18-yr-old rubber trees, Monteny et al. (1984, 1985) observed that rubber plantations give out 4 to 6 mm of water vapour daily into the atmosphere when the soil moisture availability is adequate and only 2 to 4 mm when it is inadequate. The mean estimated irrigation requirement for the dry season in the traditional rubber-growing region of India was estimated to be around 10,000 (400 mm) l for a mature tree (Vijayakumar et al., 1988) after canopy closure. Estimated irrigation requirement in the Konkan region from December to May is around 33,500 l $tree^{-1}$ (1340 mm) at a planting density of 400 trees ha^{-1}. However, comparable growth could be achieved by providing 50% of the estimated requirement (Table 2). This indicates a good adaptation of *H. brasiliensis* to water deficits.

The observed negative relation between water use efficiency and quantity of water applied (Table 2) is different from constancy of WUE reported in annual crops under varying water availability (Kramer and Boyer, 1995). Increased WUE observed in *H.brasiliensis* under lower water availability might be due to compensatory phenomenon in growth that occurs in the wet season (Fig. 1).

The lag period observed in the growth of control plants is due to severe leaf injury, reduction of chlorophyll and probably root injury experienced during the previous summer. Data showed that under the agroclimatic conditions of the region, it takes nearly 45 days for regeneration of plant parts before attaining any meaningful girth increment (Fig. 1). Data also showed for the first time the occurrence of compensatory growth in *H. brasiliensis*. Lower RGR observed even after irrigating at 1.00 ET_c (basin) in 1990 dry season (Mohankrishna et al., 1991) could be overcome once the estimated water requirement was revised. Growth rates indicate that once water stress is relieved, conditions are more favourable for overall growth in the dry season than in the wet season (Table 3). Larger relative growth rates were achieved in the 1992 dry season by applying irrigation water at the rates of 0.75 and 1.00 ET_c (basin) and were around 17%

more than the RGR achieved by the same plants in the previous wet season. Data on RGR of 1993 dry season indicate that the reduction in RGR compared to the previous wet-season values might be due to an increase in water requirement, rather higher than the estimated value. The decline in RGR with age (Table 2) is in agreement with the earlier report of Templeton (1968). Lower growth rate in drip-irrigated plants might be due to either unsuitability of the soil or to system failures.

Reduction of leaf area index under rainfed conditions is due to shedding of leaves, decrease in new leaf formation, inhibition of leaf expansion and drying of leaf margin. Increase in epicuticular wax load (EWL) on leaves is an indication of adjustment of plants to water stress so as to reduce the intensity of stress experienced. Increase in EWL under water stress has been reported in other crops (Baker, 1974; Whitecross and Armstrong, 1983; Saneoka and Ogata, 1987). Higher EWL increases reflectance leading to a reduction in heat load and leaf temperature, which results in reduced water loss and also in reduced thermal injury. However, midday leaf temperature was 3°C more in the rainfed plants compared to irrigated plants. This can be attributed to the very low transpiration rate observed. In the irrigated plants, reduction in leaf temperature is mainly due to high transpiration rates.

High rates of photosynthesis, more than what has been reported in the traditional regions (Rubber Research Institute of India, 1989–1990), were observed at 8:00 h in plants which received adequate irrigation water. Even under full irrigation, it showed reduction of more than 50% at midday. Recovery was observed in the afternoon in the basin-irrigated plants. In the rainfed plants, high stomatal resistance was observed even at morning hours and it was associated with very low values of Pn. Low chlorophyll content observed in the rainfed plants is also an important factor for the reduction in Pn (Table 7). In the partially irrigated plants also, lower level of chlorophyll and higher stomatal resistance might have contributed together to the lower rate of Pn. Decrease in photosynthetic rate with increasing intensity of water stress was reported earlier by Mohankrishna et al. (1991). Unlike in the traditional region (Vijayakumar et al., 1988), the rainfed plants showed high stomatal resistance even at morning hours. This observation is in agreement with the earlier report on semidiurnal changes in stomatal resistance of rainfed mature *H. brasiliensis* in the Konkan region (Chandrashekar et al., 1990).

Negligible growth of the rainfed plants in summer months is associated with very low turgor pressure even at 6:00 h. Lower growth achieved in the plants under 0.50 ET_c basin irrigation and in the plants under all the three levels of drip irrigation treatments is associated with lower values of turgor pressure. The values were higher in plants under basin irrigation at the rates of 0.75 and 1.00 ET_c. Osmotic adjustment was evident in rainfed plants. In plants which received irrigation water at full potential, osmotic potential was around −0.92 MPa at 6:00 h while the corresponding value in the rainfed plants was −1.35 MPa. Latex vessel water potential was low at morning in the rainfed plants and in the plants under lower irrigation regimes (T2 and T5) with simultaneous decrease of Pn. Latex vessel water potential is a clear indication of plant water status (Devakumar et al., 1988). Even though there was considerable variation in the irrigation regimes, at 6:00 h, statistically significant differences were not observed in solute potential or turgor pressure among the irrigated plants. However, statistically significant

Table 7
Correlation coefficients of physiological parameters

	Relative growth rate													
	Annual	May	Jun	Jul	Aug	Pn	Rs	Tr	TP	LSP	LAI	WAX	T_{leaf}	Chl
May	0.57[a]													
Jun	0.58[b]	0.66[b]												
Jul	0.40	−0.01	0.14											
Aug	0.00	−0.65[b]	−0.47[a]	0.37										
Pn	0.45[a]	0.87[b]	0.78[b]	−0.11	−0.66[b]									
Rs	−0.34	−0.74[b]	−0.85[b]	0.00	0.69[b]	−0.92[b]								
Tr	0.42	0.88[b]	0.7[b]	−0.15	−0.66[b]	0.96[b]	−0.83[b]							
TP	0.54[a]	0.82[b]	0.86[b]	0.13	−0.58[b]	0.82[b]	−0.86[b]	0.76[b]						
LSP	0.38	0.81[b]	0.76[b]	−0.04	−0.70[b]	0.93[b]	−0.93[b]	0.88[b]	0.87[b]					
LAI	0.45[a]	0.83[b]	0.87[b]	0.05	−0.69[b]	0.91[b]	−0.95[b]	0.83[b]	0.91[b]	0.91[b]				
WAX	−0.42	−0.80[b]	−0.87[b]	0.05	0.54[a]	−0.89[b]	0.86[b]	−0.87[b]	−0.87[b]	−0.83[b]	−0.88[b]			
T_{leaf}	−0.39	−0.55[b]	−0.73[b]	−0.07	0.56[b]	−0.77[b]	0.86[b]	−0.63[b]	−0.72[b]	−0.83[b]	−0.85[b]	0.65[b]		
Chl	0.34	0.54[a]	0.87[b]	0.11	−0.44[a]	0.79[b]	−0.87[b]	0.72[b]	0.75[b]	0.81[b]	0.83[b]	−0.83[b]	−0.80[b]	
ψ_{lv}	0.43	0.84[b]	0.81[b]	0.01	−0.69[b]	0.93[b]	−0.94[b]	0.87[b]	0.93[b]	0.99[b]	0.94[b]	−0.86[b]	−0.82[b]	0.82[b]

Pn: photosynthetic rate; Rs: stomatal resistance; Tr: transpiration rate; TP: turgor pressure; LSP: latex solute potential; LAI: leaf area index; T_{leaf}: leaf temperature on midday; Chl: chlorophyll; ψ_{lv}: latex vessel water potential.
[a]$P < 0.05$; [b]$P < 0.01$.

Table 8
Direct (diagonal) and indirect effects of physiological parameters on RGR (May)

	Photosynthetic rate	Turgor pressure	Leaf area index	Leaf temperature	Total chlorophyll	r
Photosynthetic rate	0.80	0.28	0.40	−0.24	−0.36	0.87
Turgor pressure	0.65	0.34	0.40	−0.23	−0.35	0.82
Leaf area index	0.73	0.31	0.44	−0.27	−0.38	0.83
Leaf temperature	−0.61	−0.24	−0.37	0.32	0.37	−0.55
Total chlorophyll	0.63	0.26	0.36	−0.25	−0.46	0.54

$R^2 = 0.91$; residual = 0.30.

differences were noticed in latex vessel water potential at the same time. It is evident that the plants under 0.50 ET_c basin (T2) and 0.25 ET_c drip irrigation (T5) treatments were under mild stress and that the rainfed plants (T1) were under severe stress even at morning hours. Relative growth rate of irrigated period was significantly correlated (Table 7) with turgor pressure ($r = 0.82$), osmotic potential ($r = 0.81$), and latex vessel water potential ($r = 0.84$). Among the above parameters, the latex vessel water potential may be an important indicator of the intensity of water stress.

Path coefficient analysis revealed that photosynthetic rate, leaf area index, turgor pressure and leaf temperature have direct and positive relationship with growth (Table 8). Carbon gain from photosynthesis and leaf area index was of prime importance under water stress conditions. Subsequently maintenance of turgor helps to continue carbon gain. Though leaf temperature has negative relation with growth, direct effect is positive, which may indicate it is indirectly acting through photosynthesis. In contrast chlorophyll has positive relation with growth but has negative direct effect which also indicates that chlorophyll is indirectly acting through photosynthesis.

Results of path coefficient analysis of photosynthetic rate with physiological factors revealed that latex solute potential is the major parameter affecting the photosynthetic rate under stress conditions (Table 9). Higher osmoticum in combination with higher temperature causes severe membrane damage in leaf discs of *H. brasiliensis* (Nair et al., 1995). Higher latex solute concentration (lower solute potential) can lower the photosynthesis by membrane damage. Other parameters namely, leaf epicuticular wax, turgor pressure, stomatal resistance and chlorophyll have indirect effects through photosynthesis.

Table 9
Direct (diagonal) and indirect effects of physiological parameters on photosynthetic rate

	Stomatal resistance	Turgor pressure	Latex solute potential	Leaf epicuticular wax	Total chlorophyll	r
Stomatal resistance	−0.29	0.31	−0.64	−0.48	0.19	−0.92
Turgor pressure	0.25	−0.36	0.60	0.49	−0.16	0.82
Latex solute potential	0.27	−0.31	0.68	0.46	−0.17	0.93
Leaf epicuticular wax	−0.25	0.31	−0.56	−0.56	0.18	−0.89
Total chlorophyll	0.26	−0.27	0.55	0.47	−0.21	0.79

$R^2 = 0.94$; residual = 0.24.

5. Conclusions

The present study proves that immaturity period in the subhumid climate of the North Konkan region can be reduced to 6 yrs or less by providing adequate irrigation. Tree loss and variation in girth can also be reduced significantly by irrigation. Relieving of soil moisture stress by adequate irrigation can lead to better growth performance in the dry season than in the wet season. In the North Konkan region, the mean annual estimated irrigation water requirement after canopy closure is around 33,500 l $tree^{-1}$ (1340 mm) in the dry season. However, the study shows that comparable growth can be achieved by providing 50% of the estimated requirement. Higher growth rate achieved by irrigation is associated with absence of leaf injury, increased photosynthetic rate and high turgor pressure. Osmotic adjustment was evident in the laticifers of rainfed and partially irrigated plants. The study proves absence of any direct injury due to atmospheric drought and high temperatures experienced in the region. In fact in the irrigated plants RGR was better in the dry season than in the wet season. The study indicates that reduction in photosynthetic rate and leaf area index caused by water stress is the major factor contributing to growth inhibition. The study also shows that higher solute concentration in the latex causes lowering of photosynthetic rate. In the soil type of the research station, basin irrigation is more effective than drip irrigation. Microsprinkler might be a better alternative to drip irrigation. Further studies are in progress on the irrigation requirement for optimum latex yield.

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